

**TONALITE-HOSTED AU-QUARTZ VEIN/SHEAR ZONE
MINERALIZATION IN THE ARCADIA BAY AREA,
SLAVE PROVINCE, NWT**

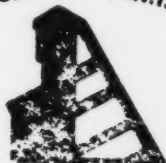
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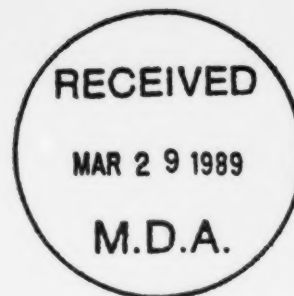
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Part 1

Principal Scientific Objectives

Four principal scientific objectives are proposed for this Ph.D. research:

1. Produce a high quality detailed lithostructural map of the Arcadia Bay area encompassing the mineralized shear zones, the sheared western contact between the Anialik River Granite Gneiss and part of the Anialik River Greenstone Belt.
- 2). Determine the petrogenesis of the tonalite-trondhjemite intrusive complex and associated "felsic dikes" to establish their magmatic affinities for comparison with the Anialik River Greenstone Belt metavolcanics and, in particular, to test Kusky's (1989) arc hypothesis.
- 3). Carry out a detailed U-Pb geochronological study of key lithologies in the Arcadia Bay Area.
- 4). Determine the nature and origin of ore fluids responsible for Archean gold mineralization in the Anialik tonalite-trondhjemite intrusive complex, and test models for the origin of Archean lode gold deposits.

These objectives were chosen for the following reasons:

1. Geological mapping of the Arcadia bay area

Accurate lithostructural mapping was necessary as a basis for systematic geochronological, lithogeochemical and petrogenetic study of the Arcadia Bay area.

Previous studies (O'Neill, 1924; Fraser, 1964; Tirrul and Bell, 1980; Yeo et al., 1983; Padgham et al., 1983; and Jackson et al., 1985) were, for the most part, reconnaissance projects mapped at scales ranging from 1:28,160 to 1:125,000. Although these provided an important background it was evident that thorough and accurate control was necessary for a detailed program such as proposed for this research. In particular, clear documentation (at scales of 1:15,000, 1:20, 1:120 and 1:500) of:

(i) cross-cutting intrusive relationships to establish relative ages of intrusions and supracrustal units; petrographic characterization of the tonalite-trondhjemite complex and associated rocks,

(ii) the extent and character of mineralization in the Arcadia Bay area; clear documentation of the characteristics of the shear zones, and

(iii) the nature of the intrusive complex supracrustal contact.

This first objective has been achieved with the completion of two summers of detailed mapping and sampling in 1987 and 1988 (Abraham 1987, Abraham and Spooner 1988a, 1988b and Abraham 1989 in progress; see maps in back pocket).

2. Petrogenesis of the tonalitic complex.

Geological mapping carried out by the author indicates that the tonalitic intrusive complex in the Arcadia Bay area is representative of the Anialik River Granite Gneiss and is petrographically typical of Archean TTG intrusive suites (Arth et al., 1978; Jahn et al., 1981; Martin et al., 1983). Petrogenetic models based on trace element behaviour have been proposed by numerous authors; the principal models for possible derivation of TTG's are shown in Table 1, Appendix A.

Proposed models for the evolution of the Slave Province (Thompson, 1978; Padgham 1985; and Kusky 1989) generally lack conclusive evidence provided by integrated geochemical petrogenetic and tectonic studies of volcanoplutonic suites, e.g. Cameron and Durham (1974), Ewing (1979), Frith and Fryer (1985) and Frith (1987) on the Hackett River volcanics, the 2.7 Ga synvolcanic tonalitic Hackett River pluton and the 2.5 Ga Regan Intrusive Suite. The last and most detailed study of the Anialik Granite Gneiss and Greenstone Belt was by Jackson et al. (1985) and, as with previous work on the Anialik, only a limited petrographic study was carried out. No published data on the geochemical characteristics of the rocks exist.

One of the fundamental objectives of the present proposed research is to evaluate the significance of the strong spatial association of gold mineralization with the Anialik tonalitic complex. If there is a genetic link between gold mineralization and the tonalitic complex it is critical to geochemically determine:

- a) whether the units mapped as representing the tonalitic complex and "felsic" dikes most closely associated with gold mineralization are comagmatic,
- b) the potential source(s) and petrogenetic history of the intrusive complex, and
- c) whether the metavolcanics are correctly identified as mapped and if they are comagmatic with the tonalitic complex.

A systematic major, trace and rare earth element, geochemical study will be carried out at the University of Toronto using standard X-ray fluorescence (XRF) and instrumental neutron activation analysis (INAA) methods (See Appendix A); major element analyses will be performed by X-Ray Assay Labs (XRAL), Toronto. Geochemical analysis will aid in

establishing the magmatic affinities of the tonalitic complex and metavolcanics in the Arcadia Bay area, and will comprise the first detailed and integrated, petrographic and geochemical study of the Anialik River Granite Gneiss and Greenstone Belt.

A combination of detailed petrography with major element geochemistry will hopefully enable classification of the mapped lithologies and determination of their petrogenetic relationships. Major element data will be plotted on standard AFM, An-Or-Ab (O'Connor, 1965; Barker, 1979), and QAP (Strekeisen, 1976; Lameyre and Bowden, 1982) triangular diagrams (Figures 1, 2, 3 and 4). A similar study of the Renabie area trondhjemite and associated rocks (Jemielita et al., 1988) showed that the granitoids delineate a trondhjemitic calc-alkaline evolutionary trend and Na-enrichment in the more evolved lithologies (Figure 5). These trends are similar to other Archean TTG rocks from the Superior Province and Archean TTG's worldwide (See Table 2, Appendix A; O'Nions and Pankhurst, 1974; Arth et al., 1978; Barker, 1979; Jahn et al., 1981; Martin et al., 1983). Data obtained from the Anialik rocks will be compared and contrasted with the above mentioned examples.

Trace element geochemistry will provide further information on comagmatic relationships, magma evolution and history, especially the less mobile trace elements Zr, Hf, Ta, and Th.

Trace and rare earth element (REE) geochemistry will provide information regarding the source of the tonalitic complex and metavolcanics, and will constrain the different petrogenetic models for Archean TTG suites. O'Nions and Pankhurst (1974) suggested that REE's, especially HREE's, should be reasonably representative of REE distribution in igneous precursors because they are considerably less mobile than other lithophile elements and patterns are unlikely to have been significantly affected by metamorphic events. However, the immobility of REE's and trace elements has been called into question and, although much of the work has been carried out on hydrothermal alteration of volcanogenic submarine exhalative ore deposits and seawater-rock interaction with sea-floor basalts (Ludden and Thompson, 1979; Finlow-Bates and Stumpfl, 1981), it has been suggested (Ludden and Thompson, 1979) that REE abundance should be used only where supported by data for immobile elements.

TTG's are characterized by moderately steep REE patterns with weak to absent Eu anomalies and low HREE values (Yb less than 8 times chondrite) (Hanson and Goldich, 1972; Arth, 1979, for further characteristics see Table 2, Appendix A). TTG's have many geochemical similarities with modern calc-alkaline magmas reinforcing the link between subduction zones and early TTG's (Bickle et al., 1983b; Campbell and Jarvis 1984).

Martin (1987) suggested that REE trends for Archean TTG's (eg. plotted on a La_N/Yb_N vs Yb_N diagram (Figure 6) can be attributed to partial melting of a hydrous tholeiitic source

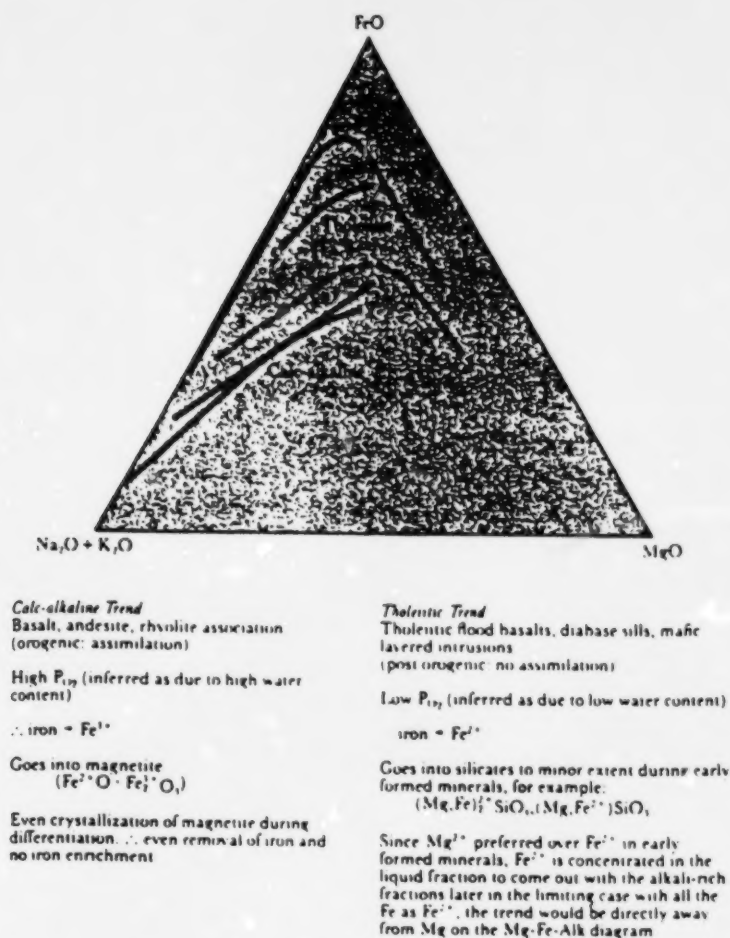


Figure 1 MgO-FeO-alkali diagram for calc-alkaline series arc volcanic rocks on continental crust from (1) Lassen Peak, northern California (Nockolds and Allen, 1953); (2) Crater Lake National Park, Oregon (Nockolds and Allen, 1953); (3) Novarupta and Mt. Katmai on the Alaska Peninsula (Forbes and others, 1969); (4) extreme iron enrichment-tholeiitic trend of Skaergaard intrusion, East Greenland, for comparison (Wager and Brown, 1968) (5) Galapagos Rift. The dotted line separates the tholeiitic series, above, from the calc-alkaline series, below, on the basis of criteria provided by Irvine and Baragar (1971).

From Hyndman (1985)

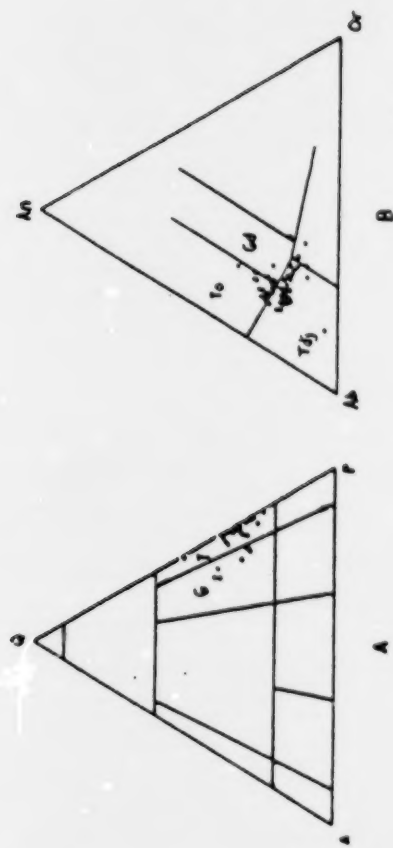


Fig. 2 (A) Modal Q-A-P diagram (Streckelsen, 1975), showing location of representative points for Archaean Finnish grey gneisses (this study) in tonalitic (T) and granodioritic (G) fields. (B) Normative An-Ab-Or diagram (O'Connor, 1965; modified by Barker, 1979 to account for K_2O content in biotites). Representative points for Archaean grey gneisses plot in the tonalite (To), trondhjemite (Td) and granodiorite (Gd) fields. The clustering of points around the triple junction of the compositional fields is typical of all Archaean grey gneisses irrespective of geographic location (i.e., TTG association).

From Barker and Arth (1976)

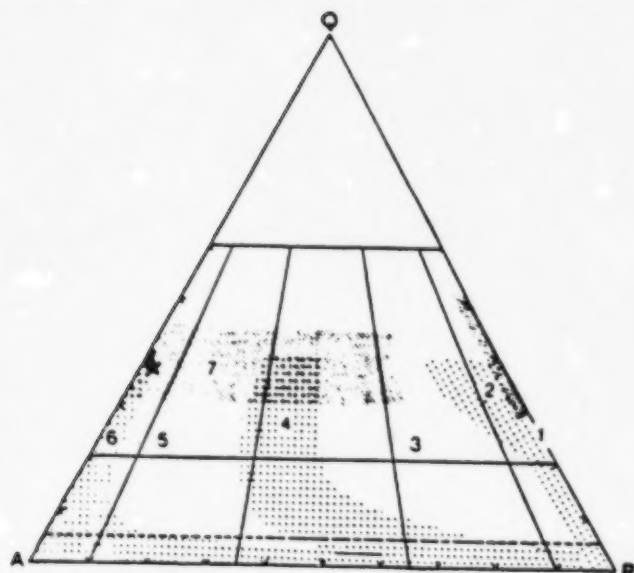


Fig. 3 Summary QAP diagram showing important fields of various granitoid series (greater than 20% vol. Q), discussed in the text: 1 = tholeiitic; 2 = calc-alkaline; trondhjemitic (low K); 3 = calc-alkaline-granodioritic (medium K); 4 = calc-alkaline-monzonitic (high K); 5 = aluminous granitoids found in alkaline provinces; 6 = alkaline and peralkaline; 7 = overlapping field of granitoids formed by crustal fusion; black star = median minimum composition.

From Lameyre and Bowden (1982)

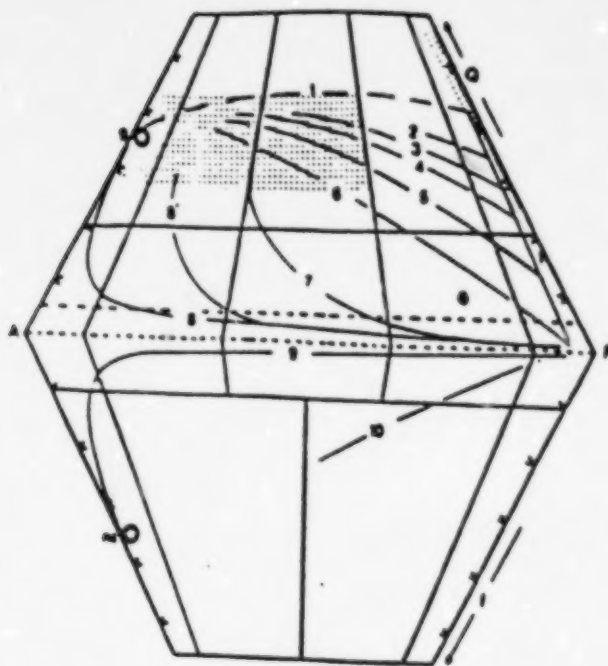


Fig. 4 Median trends in various plutonic suites: 1 = tholeiitic, Troodos, Skarsgaard; 2 = calc-alkaline trondhjemitic, S.W. Finland; 3, 4, 5 and 6 = calc-alkaline granodioritic (medium K) (3, Corsica - Sardinia (after Orsini, 1980), Chile, Peru, Sierra Nevada; 7 = calc-alkaline monzonitic (high K): Voage, Corsica; 8 = alkaline silica oversaturated trends for Niger, Nigeria, Oulo, Corsica, Kerguelen Islands; 8' = aluminous trend in Nigeria-Niger; 9 = alkaline silica-undersaturated trend: Oulo, Laacher See, Kerguelen Islands; 10 = Tahiti series. Open star (g) = granitic differentiates. Open star (ns) = nephelinitic differentiates. Shaded areas = granitic rocks of crustal origin.

From Lameyre and Bowden (1982)

RENABE	HIGHWAY 631	MAGNO
• TRONDHJEMITE	• TRONDHJEMITE	• NETWORK GRANODIORITE
• MAPIC TONALITE	• TONALITE	• SATELLITE GRANODIORITES
• SHARP TONALITE	• APLITE	• LEUCOCRATIC GRANODIORITE
• MICROTONALITE		
• PEGMATITE		
• APLITE		

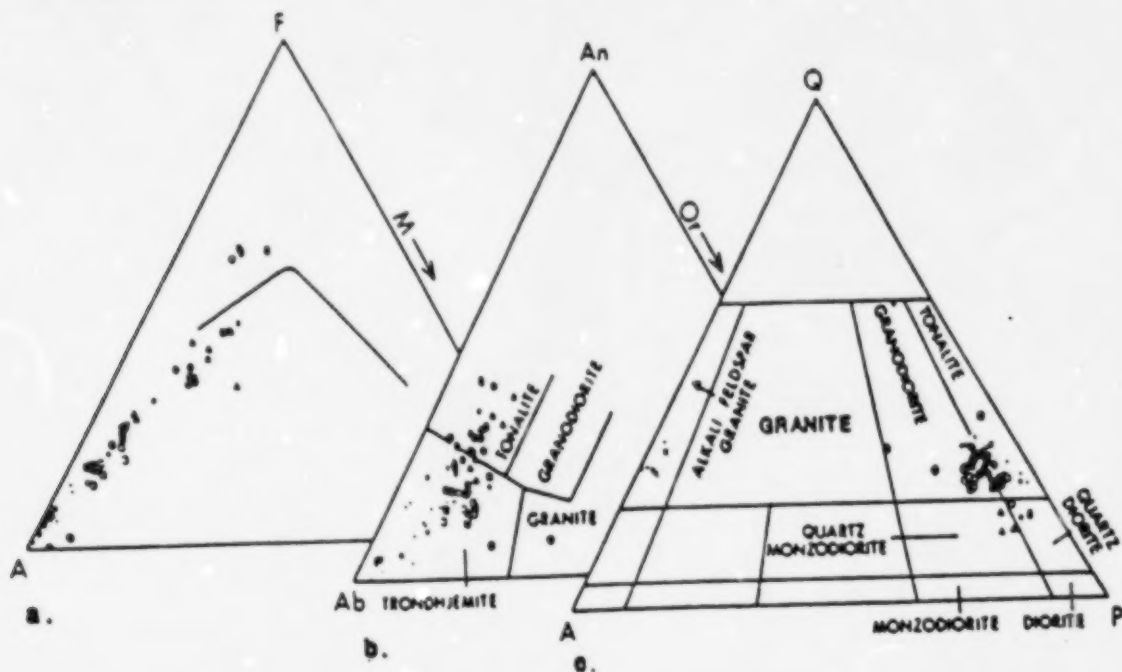


Figure 5 Major element analyses of trondhjemite-tonalite-granodiorite (TTG) lithologies from the present study plotted on (left to right): a) AFM diagram (where A = (Na₂O+K₂O), F = (FeO+Fe₂O₃ recalculated to FeO), and M = (MgO), quantities are calculated on a molecular (i.e. oxide) basis); b) An-Or-Al diagram (Barker 1979; modified after O'Connor 1985); and c) QAP diagram (after Streckeisen 1978).

From Jernielita et al. (1988)

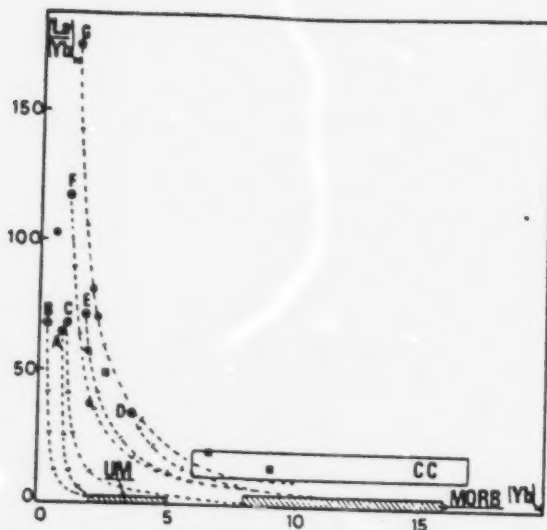


Fig. 6 $(La/Yb)_N$ v. $(Yb)_N$ diagram for Archean gneisses in East Finland: solid circles are data for the grey gneisses; solid squares are for the augen gneisses. U.M. = Upper Mantle peridotite field; MORB = Archean tholeiites and modern MORB fields; C.C. = average of the continental crust. The curves represent the trend of the composition of the liquid produced by partial melting of various source materials. These curves were calculated using Shaw's (1970) equation ($C^l = C_0/D + F(1-D)$). Star symbols represent the limiting values (zero percent of partial melting) and short bars perpendicular to the curve correspond to values of 10%, 25%, 50% and 75%, respectively, of melting source material. (A) garnet peridotite ($(La/Yb)_N = 1$ and $(Yb)_N = 4$); (B) quartz eclogite ($(La/Yb)_N = 1$ and $(Yb)_N = 4$); (C) quartz eclogite ($(La/Yb)_N = 1$ ($(Yb)_N = 13$); (D), (E), (F) amphibolites with 0%, 10% and 20% of garnet, and with initial $(La/Yb)_N = 4$ and $(Yb)_N = 10$; (G) amphibolite with 10% of garnet and with initial $(La/Yb)_N = 10$ and $(Yb)_N = 10$.

From Martin et al. (1983)

with a hornblende and garnet-bearing residue. Although garnet, and to a lesser extent hornblende, concentrate HREE's (See Table 3, Appendix A), Gromet and Silver (1983) have shown that partitioning of HREE's into allanite and sphene is enhanced as melt compositions become increasingly siliceous during crystallization of granitic systems. Miller and Mittlefehldt (1982), have shown that fractionation of LREE-rich accessories monazite and allanite controls the REE distribution and abundance during crystal fractionation and partial melting. It will therefore be important to identify and determine the paragenetic position of accessory phases in the tonalite and other rocks analyzed. Mineral separates obtained during U-Pb geochronology will be retained and accessory phases will be analyzed in detail to determine their REE concentrations.

Comparison of all the data obtained during the proposed investigation with data for Archean, Proterozoic and Phanerozoic suites will enable the author to establish a model for the evolution of the Anialik River Granite Gneiss (which hosts the gold mineralization) and Anialik River Greenstone Belt and assess its petrogenetic and tectonic relationship with the Slave Province as a whole. This work will potentially provide a significant contribution to Archean igneous petrogenesis and crustal evolution in the Slave Province.

3. U-Pb geochronology.

The relative ages of the intrusive and supracrustal rock types in the Arcadia Bay area have been established from detailed field mapping (Abraham, 1987; Abraham and Spooner, 1988a, 1988b; Abraham, 1989 in prep).

The Anialik Granite Gneiss has previously provided U-Pb zircon dates of 2.694 ± 8 Ma and 2.692 ± 2 Ma (Padgham et al., 1983) and the felsic metavolcanics of the greenstone belt have apparently provided a similar but less precise age (Padgham, 1987 pers comm.).

Precise geochronology is necessary in the Arcadia Bay area for the following reasons:

- 1) to provide precise dates for the Anialik tonalite, Chin lake Stock and "felsic dikes" closely associated with the gold mineralization.
- 2) to constrain the age of gold mineralization.
- 3) to produce an accurate time framework for the Anialik intrusive complex and the supracrustals.

Geochronological analysis will be carried out at the Royal Ontario Museum using the methods of Krogh (1973, 1982a, 1982b), and the procedure is outlined in Appendix B.

The mineralized shear zones and co-structural "felsic" dikes are hosted by the tonalite and its mafic marginal phase. The Chin Lake Stock intrudes the Anialik tonalitic complex, crosscuts the shear zones and co-structural dikes, and therefore apparently postdates the age of mineralization. It thus provides potential for bracketing the age of mineralization.

Samples of the tonalite, co-structural "felsic" dikes and the Chin Lake Stock have been collected for geochronological analysis. A new date on the tonalite is necessary because of the uncertainty of the location of the previously dated sample (Padgham et al., 1983), and hence petrographic character of the previously dated sample, and also uncertainty regarding method used (ie. single grain or batch, abraded or not, how many points used). The tonalitic complex is extremely heterogeneous in nature, but with the detailed mapping carried out by the author there is excellent control on the character and location of the samples to be analyzed.

A date from the tonalite will provide the maximum constraining age for mineralization in the Arcadia bay area, while the sample from the Chin Lake Stock will provide the minimum constraining age. Sphene is an accessory mineral associated with mineralization (eg. the #9 Vein, see Figure 14) and in the tonalite itself. A date from the sphenes will give the closest age to mineralization (if not reset by a later metamorphic event) which should fall between the maximum and minimum ages obtained from the tonalite and Chin Lake Stock, respectively. Once these ages have been established a date on the "felsic" dike will (from co-structural and cross-cutting relationships) provide evidence of their age relationship to gold mineralization. Similar studies have been carried out in the Abitibi Belt of the Superior Province (Corfu et al., 1989 in press), and this type of study has been successfully carried out by Richard Jemielita on the Renabie, Hollinger, Kerr-Addison, Lamaque and Camflo gold mines and Cornet de Ronde on the porphyries and gold mineralization in the Barberton Greenstone Belt, South Africa.

The age relationship between the Aniak tonalite complex and the greenstone belt is important with respect to the overall petrogenetic and tectonic history of the study area, in particular testing whether they are cogenetic. A sample of the quartz-feldspar porphyry unit was collected along with a possible flow unit, either of which can be used to date the metavolcanics. This research will be the first integrated geochronological, petrological and geochemical study of gold mineralization in the Slave Province.

4. The nature and origin of ore fluids.

The nature of Archean auriferous fluids has been documented in studies of fluid inclusions in Archean lode gold deposits from Canada and Australia (Ho et al., 1985; Smith et al., 1984; Wood et al., 1986; Robert and Kelly, 1987; Walsh et al., 1988; see Table 4, Appendix C). Fluid inclusion and light stable isotope data for Archean gold fluids indicate that they were relatively uniform in composition and probably generated by a uniform process from a large fluid reservoir external to the immediate depositional environment

(Colvine et al., 1988). However, available data are unable to distinguish an unequivocally unique source for the ore fluids responsible.

Although it is scientifically important to determine the chemical and isotopic character of the ore fluids and associated ore and alteration minerals in the Arcadia Bay area (for comparative purposes) it is equally essential to progress a stage further in "fingerprinting" the ore fluids with respect to a unique source. It is this latter problem that is the focus of the fourth objective of the proposed research.

As outlined above there is a broad consensus on the general character of Archean auriferous fluids, but their origin is highly controversial.

The principal proposed sources for Archean lode gold fluids are:

- 1) Lamprophyres and lamprophyric magmas (Rock et al., 1987).
- 2) Juvenile fluids formed by granulitization of the lower crust and/or degassing of the upper mantle (Colvine et al., 1988; Cameron, 1989).
- 3) Metamorphic fluids from dewatering reaction during greenschist-amphibolite-granulite metamorphism of greenstone source rocks (Kerrick, 1983; Phillips and Groves 1983, 1984; Perring et al., 1987)
- 4) Magmatic fluid source(s), TTG and/or calc-alkaline granodiorites (Wood et al., 1986; Burrows et al., 1986; Burrows and Spooner, 1987).

It is the objective of the present study to test these models with respect to the Arcadia Bay gold mineralization.

It is important to note that unlike the Australian and Abitibi gold deposits (predominantly greenstone-hosted) the Arcadia Bay deposit is hosted in tonalitic, trondhjemitic and mafic marginal rocks of the Anialik River Granite Gneiss along its western contact with the Anialik River Greenstone Belt. Mineralization occurs up to 5 km into the batholith and recent assay results suggest that gold mineralization may extend even further. There is a strong spatial and temporal association of mineralization with the marginal rocks of the batholith and co-structural "felsic" dikes within the mineralized shears (See Overview of field relations).

Fluid inclusion microthermometry and light stable isotope studies (see Appendix C) of the quartz veins, associated mineralization and alteration will be carried out to characterize the ore fluid chemistry. This will be done in conjunction with detailed reflected (and transmitted) light microscopy to determine the paragenesis of the Arcadia bay mineralization. These studies will also enable comparison with the Renabie deposit in trondhjemitic/tonalitic host rocks (Callan and Spooner, 1987; Studemeister and Kilias, 1988) and other Archean lode gold deposits.

Further to this and most importantly, I will endeavour to obtain fluid inclusion data from quartz in the least deformed phase of the tonalite, late pegmatite dikes, Salt Lake and Chin lake Stocks (Abraham, 1987). If successful, this will provide a clear indication of whether the ore fluids that produced the Arcadia Bay mineralization were derived from the tonalite and associated felsic dikes or from the quartz monzonitic intrusions. Fluids trapped in quartz in granites can either represent the earliest fluids evolved from the cooling magma or later fluids developed during hydrothermal circulation. Alderton and Rankin (1984) have suggested that both types may be trapped in apparently unaltered samples. It is generally agreed that either the magmatic or the hydrothermal stage, or both, may play an essential part in the concentration of economically important minerals (Burnham, 1979). Fluid(s) coexisting with, or evolved from, a water-saturated magma, can be trapped as primary inclusions in crystals growing from the magma, as secondary inclusions in crystals forming the wall rocks of the early fractures, or as primary or secondary inclusions in the earliest quartz filling of those fractures (Weisbrod, 1981). Examples of fluid inclusions associated with granitic-granodioritic systems have been characterized by Weisbrod (1981). Comparison of fluids found in the Arcadia Bay samples will be made with fluid inclusion data from the Tanco pegmatite (London, 1986; Thomas et al., 1988), the alkaline Ilimaussaq complex (Konnerup-Madsen et al., 1985; Konnerup-Madsen et al., 1988), the Drammen granite (Olsen and Griffen, 1984) and the Cornish granites (Bottrell and Yardley, 1988). The data obtained from this study will be the first for fluid inclusions in an Archean intrusion hosting gold mineralization.

The planned research encompassing these scientific objectives is outlined in Figure 7.

Planned Research

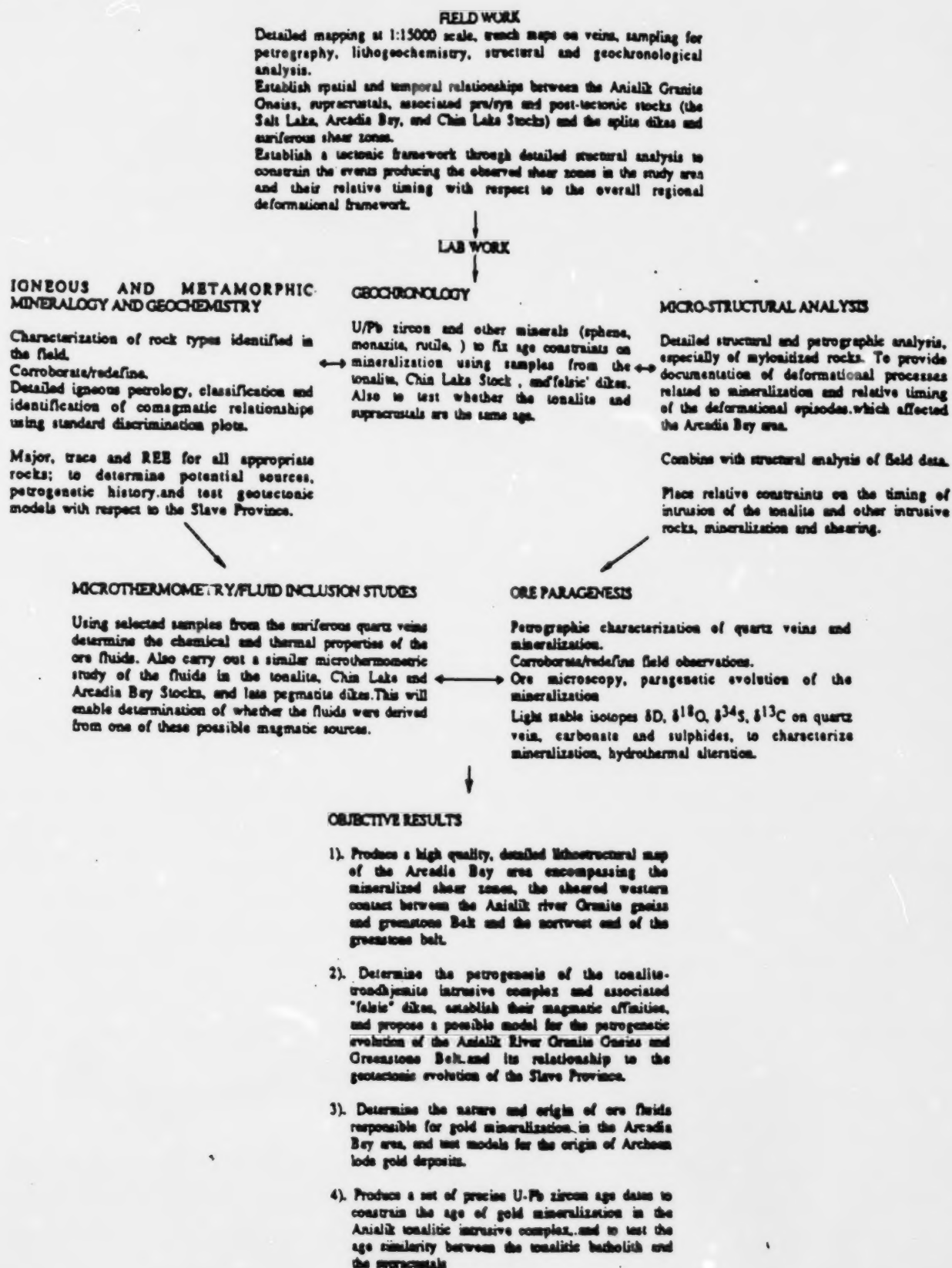


Figure 7

Part 2

Overview of the Geology of the Slave Province.

The Slave Province (Figure 8), located in the northwestern part of the Canadian Shield, is a late Archean granite greenstone terrane with components ranging in age from 3.48 Ga to 2.5 Ga (Bowring and Van Schmus, 1984; Easton, 1985; Henderson, 1985; Padgham, 1985). More recently it has been interpreted using a collisional tectonic model involving suturing of four lithostructural terranes (Figure 9) representing early continental crust, a paired accretionary prism and island arc, a back arc domain and sediments derived from arc-continent collision (Hoffman, 1986; Fyson and Helmstaedt, 1988; Kusky, 1989). The accretionary model of Kusky (1989) is summarized in Figure 10. The absence of rift-type lithological suites, predominance of contractional structures, lithologically and geochemically similar regions, the thrust-like nature of terrane boundaries, and U-Pb dates constraining events, are given as evidence for this model. In the context of the present research proposal, the author's study area is situated at the northwest end of the island arc terrane.

The Slave Province covers an area of approximately 180,000 km² and comprises the following major rock units:

- 1) ~10% Pre-Yellowknife Supergroup rocks comprising ortho and paragneisses and intrusions ranging from felsic to gabbroic in composition. These have yielded U-Pb zircon ages of 3.48-3.15 Ga (Krogh and Gibbins, 1978; Bowring and Van Schmus, 1984) with youngest ages of 2.8-2.7 Ga for quartzofeldspathic gneisses in the Sleepy Dragon Terrane (Davidson, 1972; Henderson, 1985). These lithologies form two lithostructurally distinct areas, the Anton and Sleepy Dragon Terranes (Davidson, 1972; Krogh and Gibbins, 1978; Easton, 1985; Henderson, 1985; Kidd et al., 1988; Kusky, 1987, 1988; Covello et al., 1988).
- 2) ~5% predominantly mafic Yellowknife-type metavolcanic belts (Padgham, 1985) the general stratigraphy of which is shown in Figure 11.
- 3) ~5% predominantly felsic Hackett River-type metavolcanic belts with associated 2.7 Ga synvolcanic plutons (Frith and Fryer, 1985; Padgham, 1985; van Breemen et al., 1987).

These Yellowknife Supergroup (Henderson, 1970) greenstone belts form two apparently distinct trends. The Yellowknife-type belts describe a linear trend from Turnback Lake to Takijuk lake. The Hackett River-type belts have an overall northwesterly trend along the eastern margin of the Slave Province from Walmsley

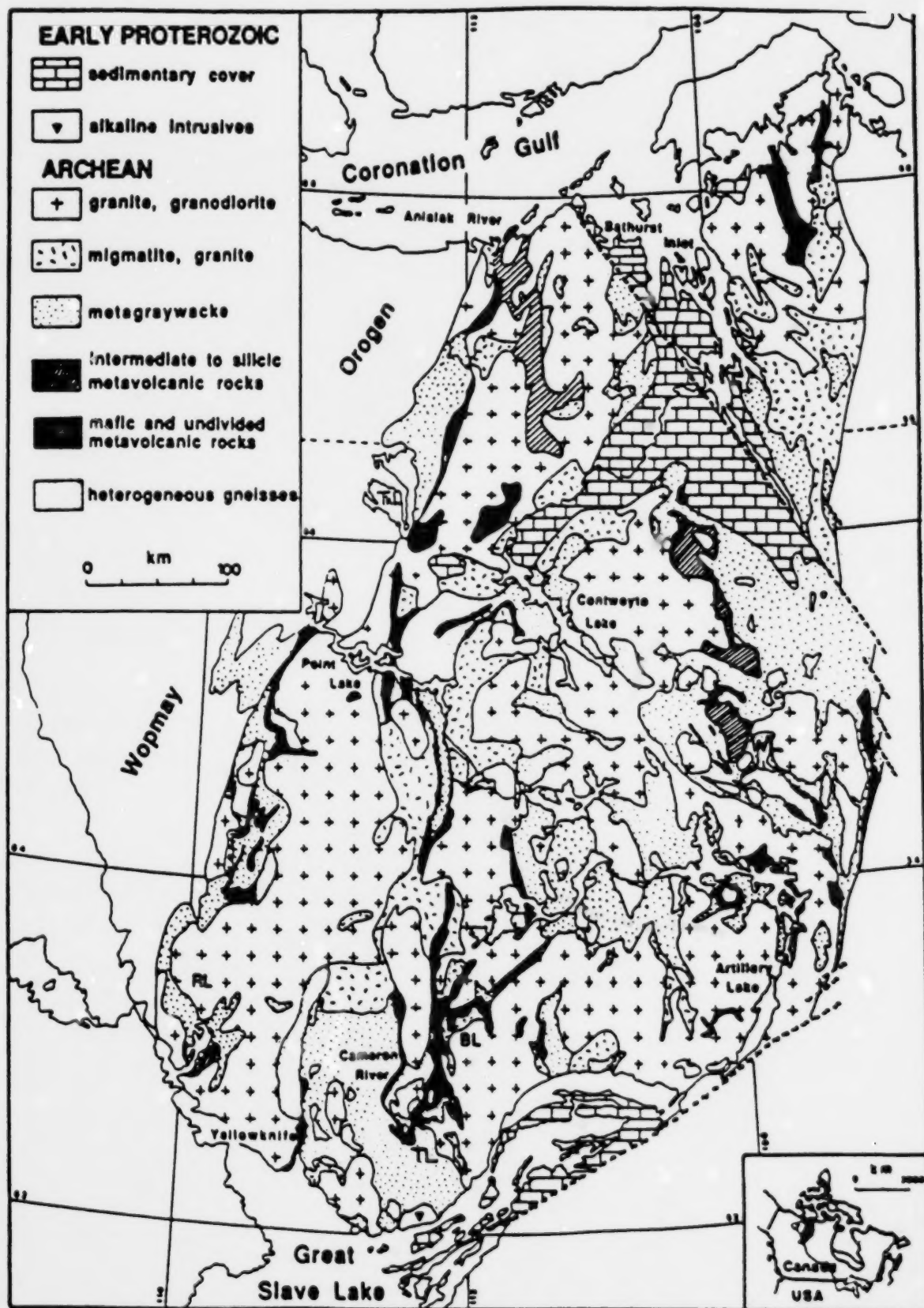
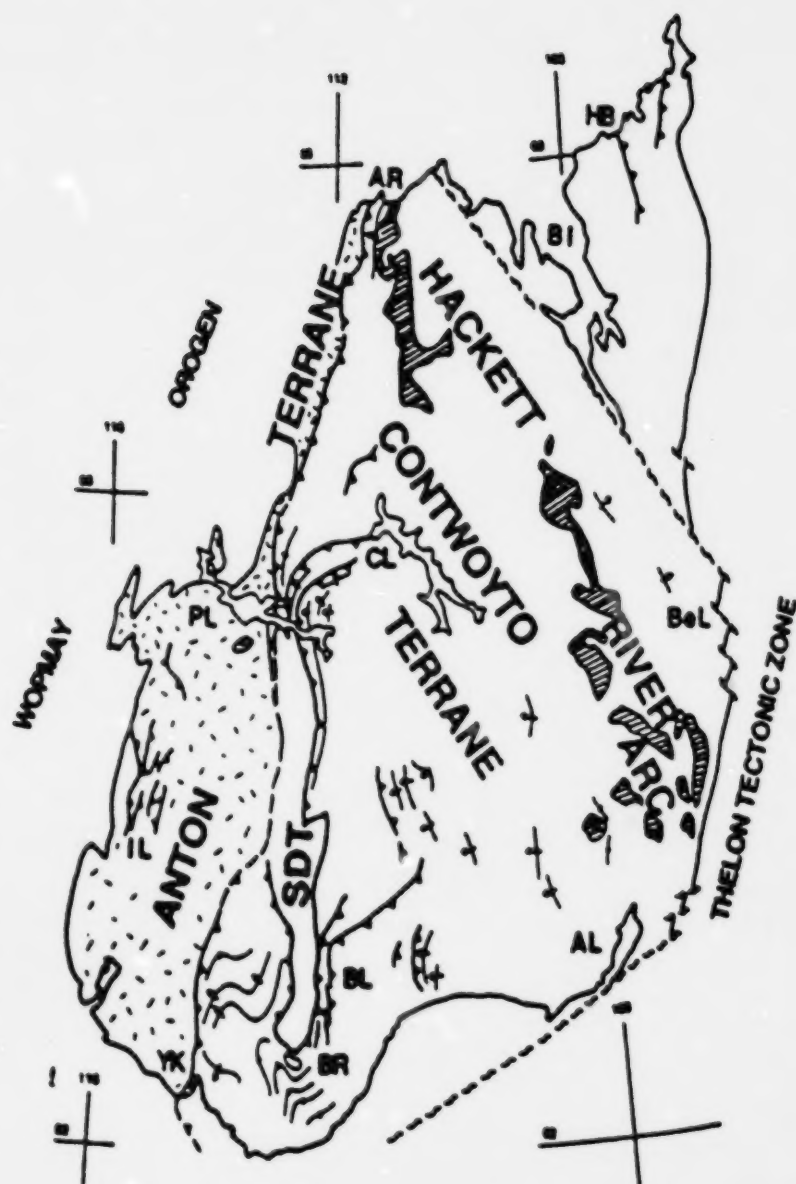


Figure 8 Geologic map of the Slave province. Modified after McGlynn (1977), Henderson (1985), Padgham (1985), and Kusky (1989). BL=Beniah Lake; RL=Russel Lake; TL=Turnback Lake; TkL=Takijuk Lake; WL=Walmsley Lake.

Figure 9. Terrane map of Slave province showing locations of Anton terrane, Sleepy Dragon terrane (SDT), Contwoyto terrane, and Hackett River volcanic arc. AL—Artillery Lake; AR—Aniak River; BeL—Beechy Lake; BI—Bathurst Inlet; BL—Beniah Lake; BR—Beaulieu River; CL—Contwoyto Lake; HB—Hope Bay; IL—Indin Lake; PL—Point Lake; YK—Yellowknife.



From Kusky (1989)

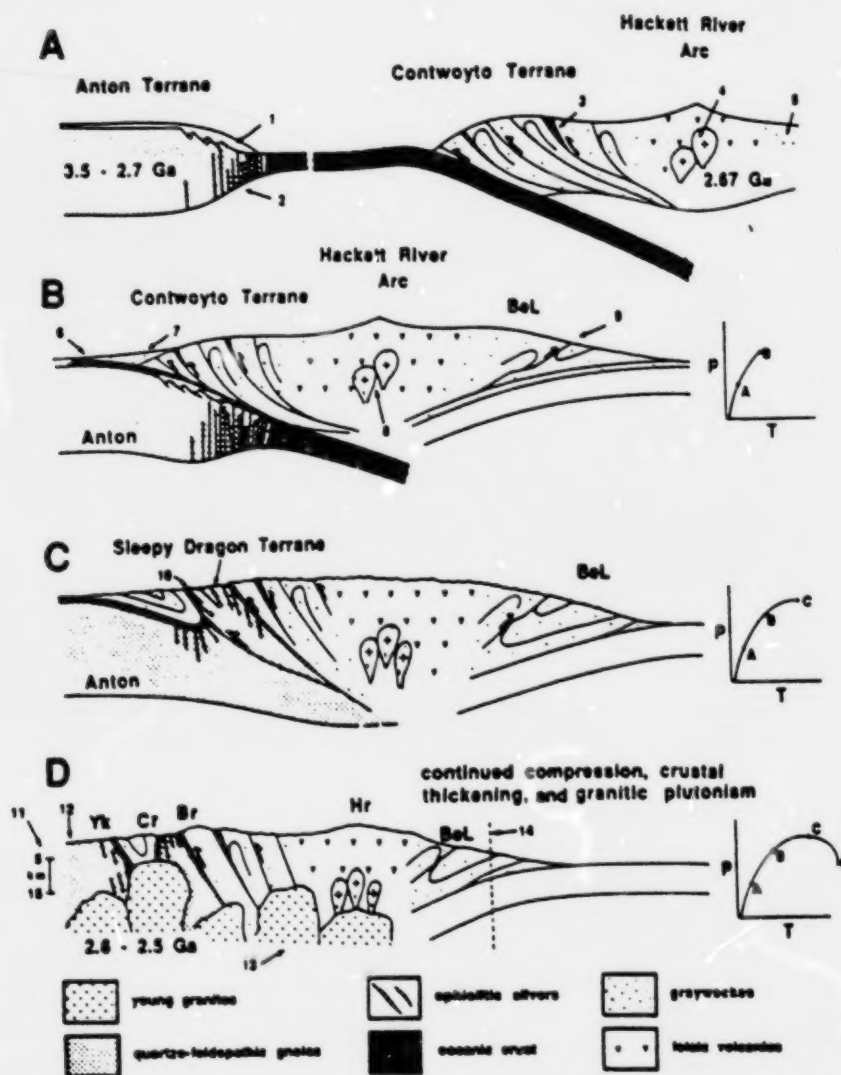


Figure 10 Cartoon showing tectonic model proposed for accretion of Slave province between 2.67 and 2.5 Ga. Bel.—Beechy Lake domain; Yk—Yellowknife; Cr—Cameron River; Br—Beaulieu River; Hr—Hackett River arc.

A. Quartzofeldspathic gneisses of the Anton Terrane, previously intruded by a set of rift related mafic dikes (2), are overlain by a thin shallow-water sedimentary sequence (1). The Hackett River Arc, with associated synvolcanic plutons (4), and the Contwoyto Terrane, including "ophiolitic" fragments (3), are formed above an east dipping subduction zone. Greywacke sedimentation (5) occurs on the backarc side.

B. Collision of the arc and accretionary prism with the Anton Terrane produces obduction of large "ophiolitic" sheets (6) and conformable flysch (7). Synvolcanic plutons (8) along the arc axis are deformed as a result of arc-continent collision, whilst back thrusting (9) takes place in the backarc.

C. Continued convergence causes uplift and transportation of the Sleepy Dragon Terrane as a basement nappe with strongly attenuated greenstone slivers (10).

D. Post-tectonic granite (13) produced by anatexis due to crustal thickening. Erosion levels range from 5-15 km (11) leaving some klippen (12). The present eastern edge of the Slave province is shown by (14) and schematic P-T paths representing the general increase in P before increase in T predicted by this model are shown on the right.

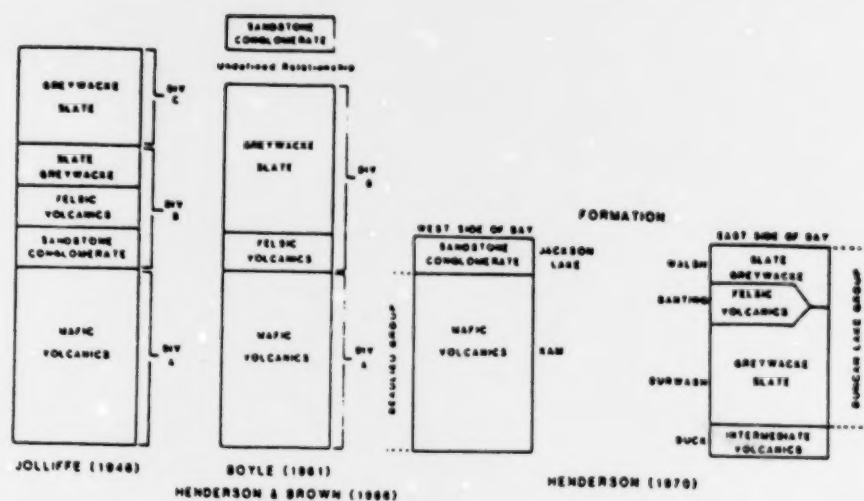


FIG. 11. Evolution of stratigraphic subdivisions of the Yellowknife Supergroup in the Yellowknife area.

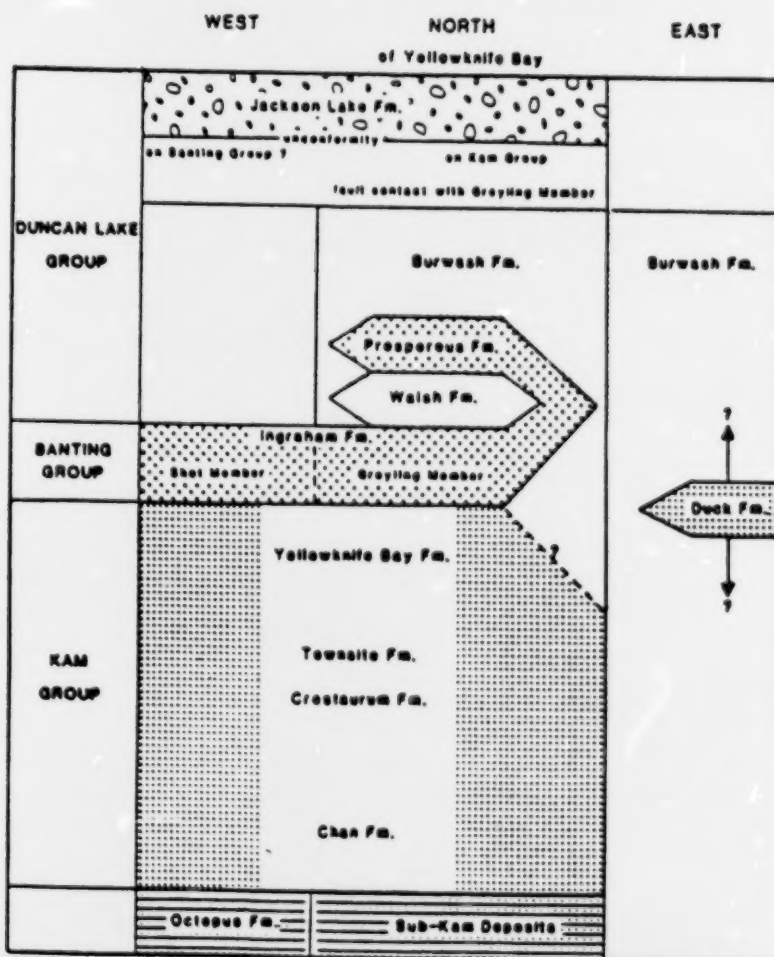


FIG. 12 Revised stratigraphic column of the Yellowknife Super-group proposed in the present paper.

lake to the Anialik River Greenstone Belt on the Arctic coast (the present study area). Kusky (1986), showed out that these distinct metavolcanic belts lie either side of a prominent Bouguer gravity anomaly. Volcanism in the Slave Province took place ca. 2.7-2.66 Ga (Henderson, 1981; van Breemen et al., 1987; Mortensen, 1988; Kusky, 1989). It is thought that the Hackett River-type metavolcanics were fed by subvolcanic tonalitic to trondhjemitic plutons (Padgham et al., 1983; Padgham, 1985; Frith and Fryer, 1985; van Breemen et al., 1987; Kusky, 1989) of which the Anialik River Granite Gneiss is characteristic. One of the objectives of the proposed research is to test this suggestion using U-Pb geochronology and igneous geochemistry.

- 4) ~25% metasediments and migmatized equivalents of the Yellowknife Supergroup. The collection of all metasedimentary rocks into this group has been called into question as it appears that two ages of sedimentation may be represented (Kusky, 1989).
- 5) ~55% granodioritic to quartz monzonitic plutonic rocks associated with the 2.5-2.6 Ga cratonization event, recently interpreted as being post-collisional anatectites produced during crustal thickening (Kusky, 1989), cross cut all rocks of the Slave Province. It is possible that the Chin lake Stock may belong to this suite of intrusion and a U-Pb date on this intrusion is therefore crucial to understanding the overall extent of late post-tectonic plutonism in the northern Slave Province.

The Slave Province exhibits five key differences in relation to other Archean granite greenstone terranes :

- i) the lower mafic volcanic group, komatiites and other ultramafic volcanic rocks which are found in most Archean greenstone belts (Condie, 1981) are invariably absent .
- ii) There is a significantly higher proportion of clastic metasedimentary rocks.
- iii) Granitic and gneissic rocks in total amount to less than the 80-90% suggested to be typical of Archean terranes (Condie, 1981).
- iv) Felsic lithologies form a greater proportion of the metavolcanics than in other Archean terranes.
- v) The ubiquity of late, post-deformational granitoid intrusions.

Reasons for choosing the Arcadia Bay area of the Anialik River Granite Gneiss.

- 1). The Arcadia Bay area mineralization is distributed throughout approximately 32 km². Almost 65% of the area mapped is outcrop and many of the quartz vein/shear systems have been trenced. This area is probably the best exposed example of Archean shear zone-hosted gold-quartz vein mineralization in its geological context in Canada, and probably one of the best in the world.

2). The shear zone gold mineralization is hosted in a tonalite and co-structurally associated with felsic dikes. These and other cross-cutting relationships provide an excellent control for U-Pb geochronological studies and an exceptional example for testing of the magmatic and other hypotheses for Archean gold.

3). The lithostructural relationships observed in the area provide an excellent opportunity to test whether the Archean Anialik tonalitic intrusive complex and felsic metavolcanics are comagmatic and arc related.

Overview of field relations in the study area mapped in 1987 and 1988.

The Arcadia Bay map area (see map in back pocket) lies at the northwestern point of the Slave Province, about 610 km north of Yellowknife, and is located on the south shore of Coronation Gulf (part of NTS 76M/11; Figure 12). The area comprises rocks of the Anialik River Granite Gneiss and the northwestern arm of the Anialik River Greenstone Belt (Tirrul and Bell, 1980) (Figure 13).

The following major features have been identified from mapping:

1) Almost half of the area mapped is underlain by a coarse grained leucocratic hornblende-biotite tonalite with subordinate trondhjemitic phases, which are heterogeneously deformed, ranging from massive to intensely foliated and locally mylonitic. This constitutes the northwestern segment of the Anialik River Granite Gneiss which has been described as an anatectic diapir intruded into the Anialik River Greenstone Belt (Padgham et al., 1983). Westward intensification in fabric sub-parallel to the margin of the tonalite, and a consequent increase in concentration of discrete zones of mylonitization, which host mineralization, both sub-parallel and oblique to the tonalite margin has been identified. The mineralized area is bounded by two major, parallel, shear zones, the western Arcadia Creek and eastern Gray's Bay Shear Zones (see map), which have strike lengths of approximately 15 km, and are 4.5 km apart. Early foliation trends in the tonalite, possibly due to diapiric emplacement of the Anialik complex, locally exhibit a sigmoidal pattern across the Gray's Bay Shear Zone consistent with a component of horizontal dextral shear. Two more regional shears, parallel to sub-parallel to these, occur to the east of the Gray's Bay Shear Zone, namely the Splitenz Lake and Anialik River Shear Zones. Dextral shear movement is also evident along these structures (Padgham, Fyson, and Jackson, pers comm., 1988) and mylonitized quartz veins may be present in the Anialik River Shear Zone (Jackson, pers comm., 1988).

2) The tonalite is subdivided into six distinct mappable units: a small lens shaped area (350 x 900 meters) of undeformed hornblende-biotite leucotonalite; local areas of intrusion breccia comprising mesotonalite blocks up to 1 meter in size in leucotonalite; zones of leucotonalite

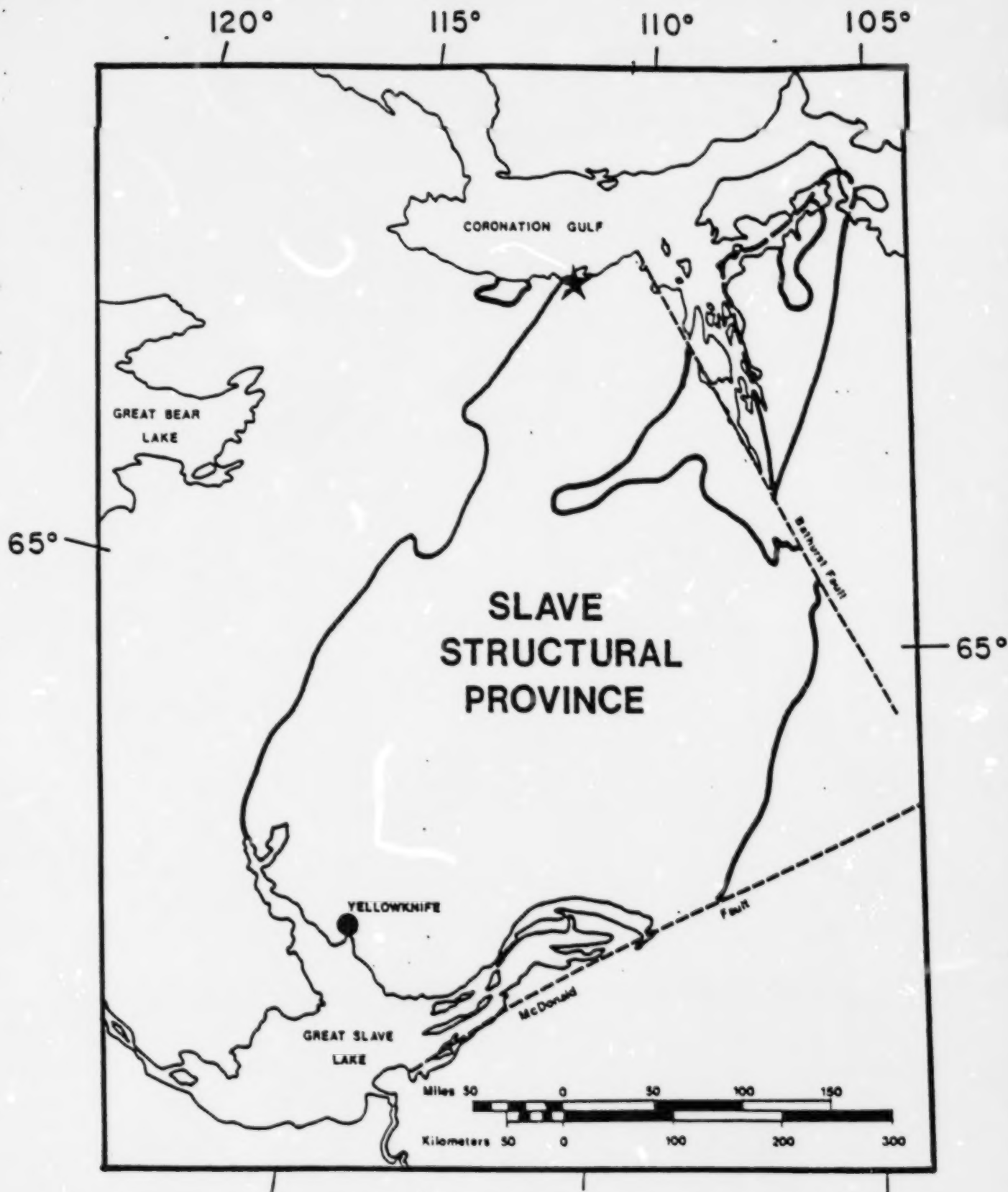


Figure 12 Location of the Arcadia Bay Property N.W.T.

★ Arcadia Bay Property

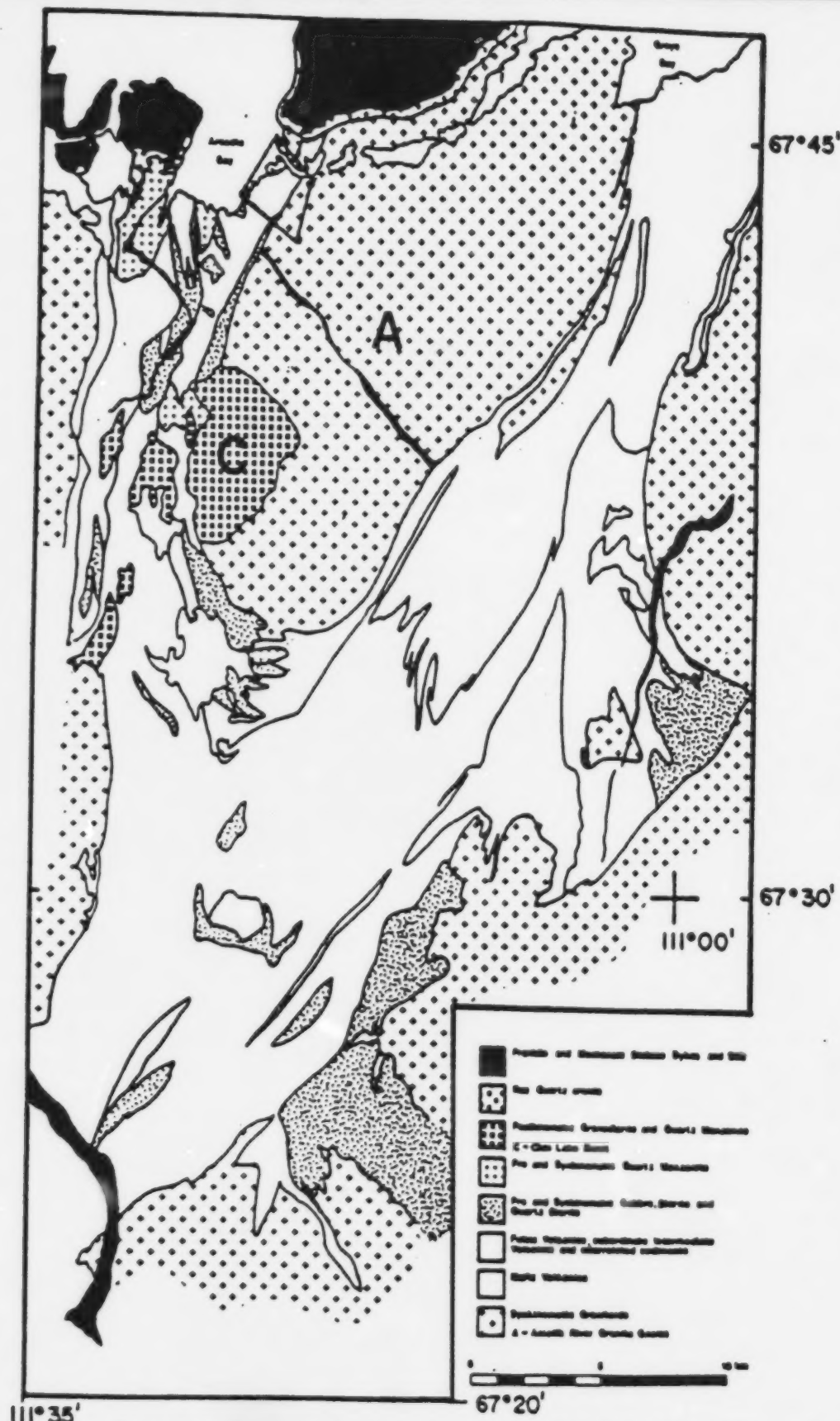


Figure 13 Simplified geological map of the Aniak River Greenstone Belt
Modified from Tirul and Bell (1980) ,

with thin mesotonalite schlieren; mesotonalite; "mixed" zones, predominantly mesotonalite with leucotonalite injections and dikes; and a mafic marginal phase. The heterogeneously, but predominantly intensely, deformed mafic marginal phase is also subdivided and appears to be a tectonically modified gradation from mesotonalite through diorite into gabbro.

3) The Anialik tonalite is intruded by numerous dikes of mafic, intermediate and felsic composition. The least abundant are north and west trending, fine to medium grained, mafic dikes of gabbroic composition, which are intensely foliated and altered.

Grey weathering, predominantly fine grained, locally porphyritic, dikes of intermediate composition are more widespread. These are strongly to intensely foliated, range in width from under 10 cm up to 2 m and commonly occur in zones (up to 50 m wide and up to 800 m long) of clustered, disrupted blocks which may be a product of folding and boudinage. These intermediate dikes are themselves intruded by later, pink weathering "felsic" dikes which disaggregate already disrupted blocks and also cross-cut and intrude along their margins.

The most common discordant intrusions are the "felsic" dikes. "Felsic" dikes (granodiorite/tonalite, granite, microgranite, aplite, pegmatite and quartz-feldspar porphyries) are predominantly intensely deformed and exhibit good cross-cutting relationships. The earliest dikes (usually less than 30 cm wide on outcrop) are north to northeast trending, grayish to pink weathering, medium to coarse grained, strongly foliated and folded granodiorite/tonalite. Later granite, micro-granite, pegmatite and aplite dikes cross-cut the early phase dikes and also one another. Those with an approximate 030° trend are commonly parallel or subparallel to the mineralized shears and incorporated into them. Distinguishing between the various mylonitized dikes, and tonalite is difficult especially where hematite alteration and silicification obscures relationships. However, dikes typically exhibit sharp rather than diffuse margins. Late syntectonic, cross-cutting, mineralized dikes (usually less than 0.5 m wide on outcrop) within the shears are common and may contain as much as 3% pyrite as disseminated euhedral crystals, 1-2 mm in size. Dikes distant from the shears and mineralization are invariably barren and carry only trace pyrite. The 030° trending dikes are commonly cut by a later set of 045° trending granite and pegmatite dikes that are less intensely foliated and appear to be sparsely mineralized. All the aforementioned dikes are cut by late syn-tectonic, typically northwest trending, garnet-bearing aplites and pegmatites (ranging in size from less than 5 cm up to 2 m wide) which exhibit possible alignment of crystal growth parallel to the foliation in the tonalite and poorly developed boudinage.

Rare, late synkinematic quartz-feldspar porphyry dikes occur in the mafic marginal zone where they cross-cut earlier dikes and fabrics but are themselves deformed by the north to

northeasterly shears. These dikes become more prevalent in the "Sheeted Zone" (see later) and supracrustal belt.

4) Supracrustals in the Arcadia Bay area are predominantly felsic metavolcanic, but approximately 50% of the supracrustal belt mapped comprises a large, possibly synvolcanic, quartz-feldspar porphyry intrusion. Metavolcanics also include: felsic tuffaceous and fragmental units; subordinate intermediate flows and/or sills, fragmentals and tuffaceous units; minor mafic volcanic rocks, comprising amygdaloidal, phyrlic and variolitic flows, and tuffs; and minor intravolcanic sediments sparsely distributed throughout the belt.

5) The supracrustals are intruded by two large gabbro intrusions (Golfing Lake Gabbro, Abraham and Spooner, 1988) and related northerly trending gabbro and diorite dikes. The gabbro and associated dikes are meso to melanocratic, medium to coarse grained and heterogeneously deformed and altered. Chilled margins are not apparent along contacts of the large gabbro bodies, but dikes exhibit well developed chilled margins up to 2 cm wide. The gabbro intrusions cut across the large quartz-feldspar porphyry and are themselves cut by a second phase of quartz-feldspar porphyritic dikes similar to the larger intrusion.

6) The Golfing Lake gabbro and the volcanics are intruded by pink weathering, quartz-rich, coarse grained, strongly lineated, locally porphyritic quartz monzonites, the Salt Lake and Arcadia Bay Stocks (Abraham, 1987; Abraham and Spooner, 1988). Their intrusive relationships, continuity of shear zones in the volcanics across their margins, coupled with the strong linear fabric development supports a pre-tectonic emplacement.

7) Dark greenish to black weathering, fine grained, intensely foliated mafic dikes crosscut the supracrustals and the Salt Lake and Arcadia Bay Stocks.

8) All rocks in the supracrustal belt are intruded by a suite of predominantly northerly trending, pink, fine grained, up to 2 m wide, quartz and quartz-feldspar porphyritic felsic dikes which are also found in the "Sheeted Zone" (Abraham and Spooner, 1988) and mafic marginal rocks of the tonalite.

9) The contact between the Anialik tonalite and the supracrustals is defined by a 200-800 meter wide high strain zone, the "Sheeted Zone". The "Sheeted Zone" comprises schistose to mylonitized, (typically dark green weathering, chloritized and epidotized) equivalents of the mafic marginal phase of the tonalite and appears gradational into highly strained felsic

volcanics to the west. The intensely deformed mafic intrusives are themselves intruded by numerous, pink to white, "felsic" dikes (ranging in width from less than 5 cm up to 2 m) parallel and subparallel to the foliation of the high strain zone, and locally making up approximately 80% of its width. Jackson et al. (1985), recognized a similar zone of felsic dikes along the the south and eastern margins of the batholith.

The dikes deformed mafic intrusives and felsic volcanics are tight to isoclinally folded about steeply dipping, north to northeast striking axial surfaces. These folds (ranging in wavelength from a few centimeters to 7 meters, with amplitudes of up to 30 meters) have moderate to subvertical plunges predominantly to the south and southwest; north to northeast plunges have also been observed. Linear fabric development appears to be absent in this high strain zone and it is interpreted as a zone of intense flattening initially produced during emplacement of the Anialik River Granite Gneiss into the supracrustals and subsequently reactivated during regional deformation. The supracrustals to the west of the "Sheeted Zone" represent a domain of pervasive linear fabric development (predominantly subvertical west to southwest trending) characterized by streaked and rodded quartz and feldspar phenocrysts, in the large, probably synvolcanic quartz-feldspar porphyry intrusion, and preferred orientation of long axes of deformed volcanic fragments observed in fragmental units marginal to the porphyry. A possible model that combines regional shear movement and high strain flattening is that flattening took place prior to and was locally overprinted by translation.

10) The northern margin of a discordant, post-tectonic, apparently unmineralized, quartz monzonite, the Chin Lake Stock (Abraham, 1987), intrudes the supracrustal belt, tonalite intrusion complex and related dikes, and cross-cuts major shear structures that extend to the southern part of the mapped area (ie. the Gray's Bay Shear Zone and subsidiary mineralized shears). The contact of this predominantly coarse grained, massive and pink to red weathering quartz monzonite is sharp with minor occurrences of xenoliths and no associated dikes traceable from it.

Characteristics of mineralization

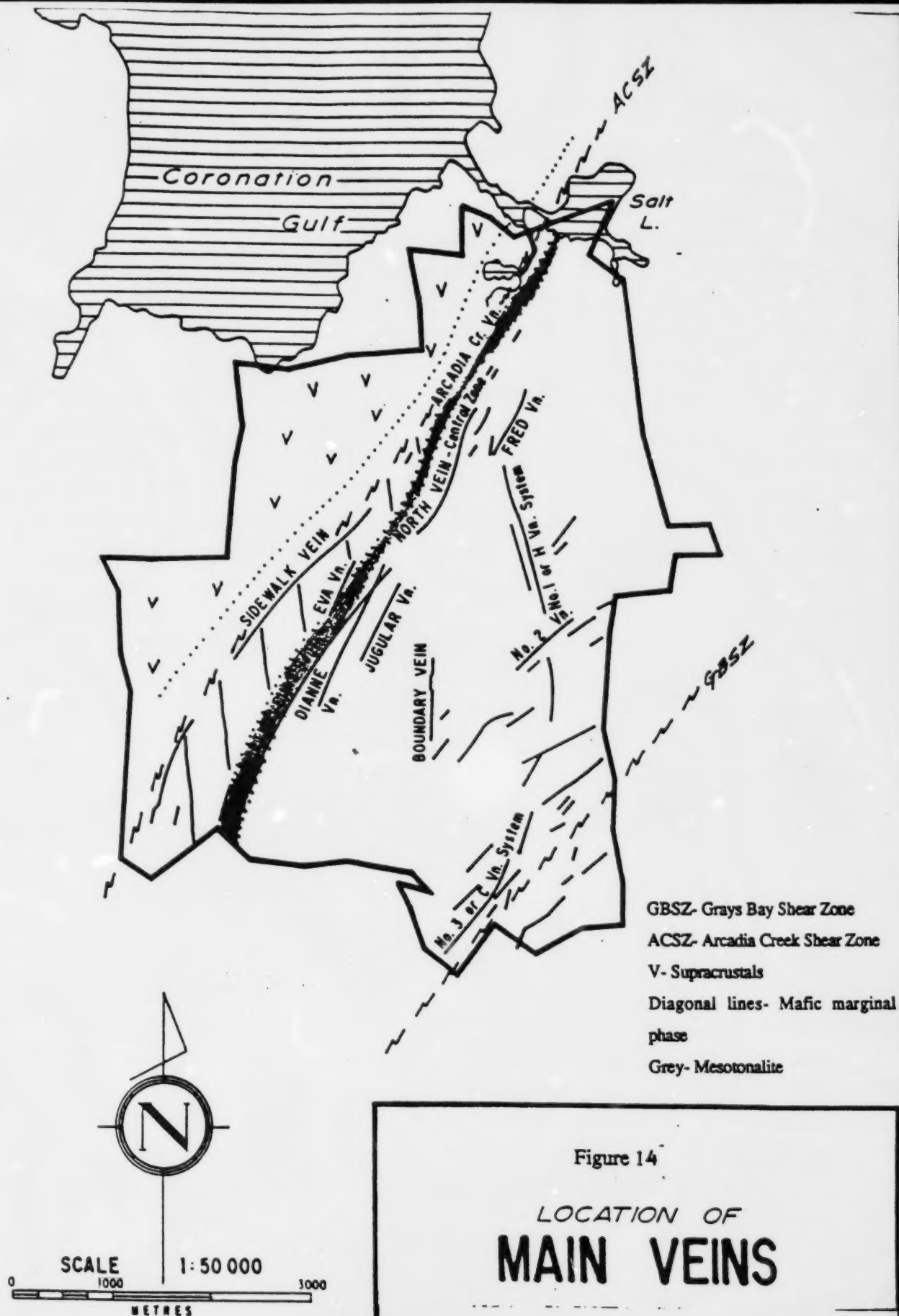
Mineralization (860,000 tons grading 0.22 oz Au/t, Northern Miner, October 31st 1988), occurs in an approximately 32 km² area in the strongly to intensely foliated tonalite and marginal mafic rocks of the western Anialik intrusive complex. It is predominantly hosted by longitudinally extensive (up to 5 km strike length) brittle/ductile shear zones containing mylonitized tonalite, associated mafic phases, and "felsic" dikes and quartz veins. Two principal sets of shears are recognized; a north to northeasterly trending set (predominantly 030° trending eg. North Central, Sidewalk and C-vein systems) and a north-northwesterly trending set (~345°

trending, eg. H-vein and Boundary Vein systems), see Figure 14. Although quartz veins appear to be strike extensive as well, it is important to note that they are in many cases closely spaced en echelon shear-type veins.

Ore mineralogy comprises predominantly pyrite with subordinate chalcopyrite, molybdenite, galena and sphalerite within quartz, quartz-carbonate veins and mylonitized tonalite, diorite, gabbro and "felsic" dikes. In hand specimen gold (1 mm size specks) is seen in granular aggregates of deformed pyrite in the early quartz, and in thin section as fracture infilling in the deformed pyrite

Three stages in the development of the quartz veins are recognized;

- a) An early synkinematic, intensely sheared streaky grey quartz which cross-cuts early felsic dikes and fabrics. It commonly contains highly deformed pyrite, either as massive granular aggregates of crushed relict subhedra, or as tails of broken redistributed pyrite parallel to the shear zone walls. Molybdenite occurs as a pale metallic blue-grey "paint" on sheared quartz. Galena has a dull grey appearance and occurs as highly deformed "paint" or in pressure shadows of deformed pyrite.
 - b) Main stage, less deformed, white, grey or buff colored quartz which typically contains large euhedral pyrite, and small sparsely disseminated aggregates of galena, molybdenite, chalcopyrite, sphalerite and buff coloured carbonate. It also contains silicified and hematite altered fragments of wall rock (typically mylonitized tonalite and "felsic" dikes). Hydrofracturing is commonly associated with this stage of quartz.
 - c) Late post-deformational infilling of fractures in the quartz vein-mineralization/shear systems is represented by vugs rimmed by clear, white and pink euhedral quartz and infilled with white or brown weathering carbonate. These quartz filled vugs are often red stained due to late hematite alteration.
- Mineralization in the supracrustal belt and related intrusions is sparse, but a number of areas of economic potential are evident:
- i) Pyritic gossaned zones in the fine to very fine grained felsic tuffaceous rocks and some of the chloritic schistose units.
 - ii) Mineralized (predominantly pyrite) shears and aplitic dikes in the Salt Lake and Arcadia Bay Stocks
 - iii) Minor shears with sulfides occurring in the Golfing Lake Gabbro.



Conclusions

The planned research objectives outlined in this proposal will make fundamental scientific contributions to the understanding of the following:

- 1) The origin of Archean lode gold ore fluids.
- 2) The petrogenesis and geochronology of Archean TTG intrusive suites, associated felsic metavolcanics, and more specifically provide a better understanding of the evolution of the Hackett River-type metavolcanics.
- 3) The tectonic implications of (2) with particular emphasis on testing the arc-accretionary tectonic model in the Slave Province.

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Appendix A

Table 1 Petrogenetic Models for Archean TTG's

Model and references	Processes involved	Geochemical constraints
Fractional crystallisation (FC) of a basaltic magma.eg.Arth et al. (1978), Gabbro-diorite-tonalite-trondhjemite suite of southwest Finland.	Proposed removal of hornblende in the production of a gabbro to tonalite suite. More silicic tonalites and trondhjemites would involve biotite and plagioclase. Helz (1973, 1976) experimental melting of tholeiitic basalts at $P_{H_2O} = 5\text{kb}$ produced trondhjemites and tonalites.	Arth et al. (1978) state the observed presence of cumulate rocks and compositions ranging from 42-74% SiO_2 is strong evidence for FC.
Partial melting (PM) of eclogites or basic granulites. Green and Ringwood (1968; O'Nions and Pankhurst (1974, 1978); Compton (1978); Longstaffe et al.(1982); Rudnick and Taylor (1986).	Two stage melting model Hydrated slab (garnet amphibolite or pyroxene granulite with 15% garnet) undergoes small degree of PM to produce melt enriched SiO_2 , K_2O , H_2O and REE's. This rises into overlying mantle wedge and enriched mantle subsequently melts to produce Calc-Alk. magmas. $P > 25\text{kb}$ needed for PM of eclogite.	REE patterns consistent with equilibration with residual garnet. therefore simplest interpretation is that they represent PM of garnet-bearing assemblages. Johnstone and Wyllie (1988), presented experimental data (phase relations of natural trondhjemite at 15kb @ $610^\circ\text{-}1100^\circ\text{C}$) consistent with the three stage model of Jahn et al. (1984).
Partial melting (PM) of amphibolite +/- garnet (basaltic source with short crustal residence time) Barker and Arth, (1976); Martin et al. (1983)	PM (25-75%) of garnet-bearing amphibolite already enriched in REE's	Sr and Nd isotopic data preclude derivation from older continental material. Using $(\text{La}/\text{Yb})_N \text{ v } (\text{Yb})_N$ diagram discriminates against other sources (Martin et al., 1983b.

Open-system fractional
crystallisation MARCY model
of Kramers, (1988)

Magma in a near-surface partially
molten zone converges above mantle
sinks and undergoes FC Recharged
fractionating reservoirs would form at
sites of convergence; magmas evolve
towards TTG-type compositions.
Magma oceans regarded as steady state
reservoirs produce tholeiitic cumulate.
Still invokes a two stage model but
without subduction. Concludes with aid
of data from Helz (1976) that the
steady state composition of the
recharged fractionating reservoir (with
amphibole being a significant
fractionating phase) is tonalitic to
granodioritic.

MARCY model does not require a small
% of PM to reproduce the trace element
characteristics of Archean TTG's. Model
also predicts initial Sr, Nd, Pb, etc
values similar to primitive mantle at
time of consolidation.

Rutile TiO_2

Nb, Ta due to close similarities in ionic radius between Ti^{4+} and both Nb^{5+} and Ta^{5+} . Dominating importance in the mid to heavy REE's.

As with Allanite, Gromet and Silver (op cit) found that Sphene also contains 80-95% of each REE in the Peninsular range Batholith, and also exhibits REE zoning. Core to rim decrease in Ce of ~50% is suggested to represent a similar decrease in the melt.

Sphene

$\text{CaTi}(\text{SiO}_4)(\text{O},\text{OH},\text{F})$

The principle substitutions are Ca for most REE's and Ti is replaced by Nb, Ta, V, and Cr.

Green and Pearson (1987), show that $D^{\text{Sphene-liq Nb Ta}} >$ with $<T^\circ\text{C}$ not significantly affected by P in range 7.5-16kb. Also unaffected by $f\text{O}_2$ variation corresponding to the HM and -MW buffers at 1000°C with variable P Also $D^{\text{Sphene-liq Nb Ta}}$ generally $>$ with SiO_2

Monazite

$(\text{Ce La Th})\text{PO}_4$

Ce, La and most LREE's

REE's especially LREE's therefore produces LREE depletion (Rapp et al., 1987)

Apatite

$\text{Ca}_5(\text{PO}_4)_3(\text{OH}, \text{F}, \text{Cl})$

Y (in synthetic apatites) but it only averages 0.1-1% by vol of rock composition so not a strong depleter.

Hanson, (1978), has suggested that Apatite has large K_D 's for REE's, causing depletion of middle REE's and contributing to a +ve Eu anomaly if present in sufficient quantities

Stix et al., (1988) state that LREE's are not essential structural constituents, therefore bulk distribution coefficients of LREE's due to apatite are considerably small $\ll 1$.

See Stix et al., 1988 table 5 page 6145.

Ilmenite FeTiO_3

Similar to rutile

Chevkinite

$(\text{Ca Ce Th})_4(\text{Fe}^{2+} \text{ Mg})_2(\text{Ti Fe}^{3+})_3(\text{Si}_4\text{O}_{22})$

Ce and other LREE's

See Stix et al., 1988

Garnet

$Mn_3Al_2Si_3O_{12}$

Y. Yttrium-bearing garnets (spessartines (Mn-garnet) are restricted to granite pegmatites Mn replaced by Y

Garnet has very small KD's for LREE's but large KD's for HREE's (>Cpx and Hb). Garnet contributes to =ve Eu anomaly when present in large quantities (Hanson, 1978).

Plagioclase

Depletes melt in Sr, with decrease in fO_2 and T°C Eu anomaly increase. Eu is the key REE affected by plagioclase (Hanson, 1978).

Hypersthene.

Leads to melts with slightly more enriched LREE's than HREE's and contributes to a +ve Eu anomaly.

Clinopyroxene

Less depletion of HREE's relative to hypersthene and contributes to a +ve Eu anomaly

Hornblende

KD's for Hb > Cpx.

The main affect of Hb on REE's is in depleting the middle and less so the HREE's, and contributes to a +ve Eu.

Appendix B

Geochronology

There are eight major steps in the procedure of geochronological analysis:

1. Sample collection
2. Crushing and powdering.
3. Magnetic and heavy liquid mineral separation.
4. Mineral picking.
5. Abrasion and cleaning.
6. Weighing and dissolution.
7. Chemistry.
8. Mass spectrometry.

Sample collection.

Geologically critical samples are collected from which you expect to obtain dateable minerals. Samples collected must be critically constrained in the map area and shown to be of geological importance to the study.

Between 70-100 lbs. is a normally needed for each sample, although in some cases where dateable minerals are visible in sufficient quantities less weight is obviously the norm.

Crushing and powdering.

Samples are inspected and all weathering, extraneous veins and contamination removed.

They are reduced to fist-sized lumps or smaller then put through jaw crusher and reduce to gravel size. This is then ground down to sand size (ca. 100 mesh) in a rotating disc mill. Crushings is carried out under conditions of the strictest cleanliness with repeated washings of the room and equipment and all material is placed in plastic bags on site. This procedure, if done correctly, ensures minimum contamination.

The sand fraction is passed over a Wilfley table which separates light from heavy minerals and as potentially dateable minerals zircon, monazite, baddelyite, rutile, sphene, along with apatite, hornblende, pyroxene, magnetite, ilmenite, and sulfides, are typically found in the heavy fraction this is collected whilst the light fraction, which is rerun 3-4 more times to collect all heavies, is rejected.

The heavies are rinsed in alcohol and dried on a hot plate under infra-red lamps.

The rinsed and dried fraction is placed on a vibrational stand and run through a 70-mesh sieve.

Magnetic and heavy liquid mineral separation

The sieved minerals are dropped vertically past a Frantz magnetic separator (wrapped in brown paper to ensure against loss and contamination) with the current at full field. This pulls out all magnetics (magnetite, iron from crushing process etc.) and the non-magnetic residue is collected below and taken to the next stage of separation. The magnetics are retained and labeled.

The non-magnetic fraction is placed into a separating flask containing the heavy liquid Bromoform (CH_3Br). Quartz and feldspar float and are separated. Once separated clean both the light and heavy residue are rinsed in alcohol before drying as before.

The Frantz Isodynamic Separator is arranged with a slight forward tilt and minerals are passed through at various amperages (0.25, 0.5, 1.0, and 1.7 Max=Full Field). The non-magnetic fraction from each pass is removed and passed on to the next higher amperage. Collect each fraction (magnetic) label and store, the last full field fraction is the non-magnetic. This non-magnetic fraction is put into Methylene Iodide (CH_2I_2). The remaining heavy and light non-magnetic minerals are separated in the flasks and funnels. Separates are again wash very carefully in alcohol (Methylene iodide fumes are even more deadly).

Set up the final Frantz Separation which is always at full field (1.7 Amps). The front to forward angle of the separator is varied from 5° , 3° , 1° , and 0° the last pass will leave you with the least magnetic separates, each separate is bottled and labelled.

Mineral picking

The least magnetic or non magnetic separates are taken to the picking lab where a small sample is placed carefully onto a new clean petri dish add alcohol and inspect under a binocular microscope. Using very sharp tweezers pick the best looking zircons (diagnostic morphology, no turbidity, cracks, cores (unless specifically of interest) or inclusions). You can run a single grain or a suite, always select your best, and always photograph the fractions used.

Abrasion

The samples are then placed into the abrader (Figure 15), a little pyrite powder (for zircon only) is added and the abrader is sealed before attaching the compressed air.

This is done to abrade off any excess radiation damage and outer zones of later mineral growth, because these areas may be leached of U/Pb.

Abrasion is run for up to two to six hours at between 2.5-4.5 psi checking every half hour, this depends on the hardness of the mineral being used. Rutiles and sphenes are treated similarly but pyrite is not used and they are abraded for only 15-30 minutes. The resultant grains are typically "jelly-bean" or spherical in shape. (Figure 16).

Weighing and dissolution

Dissolution and chemistry of zircon, baddeleyite, rutile, and monazite follow methods of Krogh (1973). Before weighing the grains have to be cleaned of any pyrite and common lead contamination picked up in the process of picking.

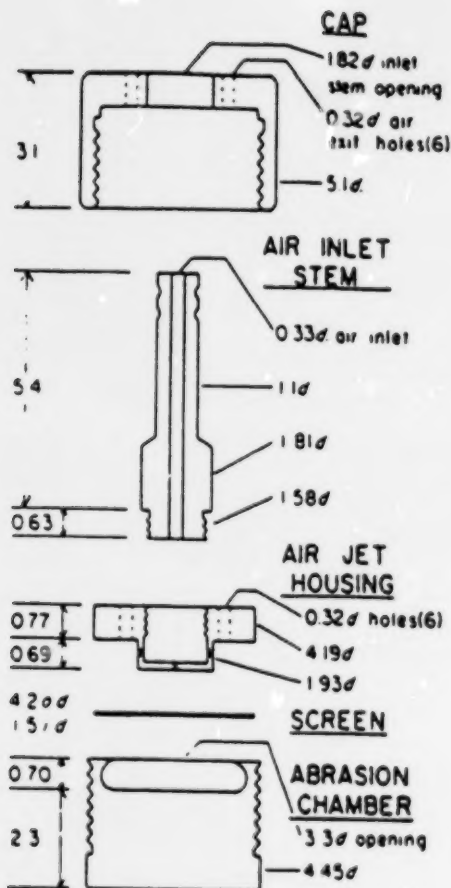


FIG.15 Air abrasion device. Abrasion by impact at high input air velocity, or polishing with pyrite at low air velocity is achieved in the lower chamber as air enters through the three (1 mm) tangential holes in the air jet housing. The sample is retained by a disposable nylon sieve force fit over the housing, usually with 20 to 40 μ m openings. The top of the air inlet stem is connected to a regulated compressed air supply usually operated at 2 to 5 psi. *d* represents diameter in mm.

From Krogh (1982b)



FIG. 16. Typical clear, low colour, crack-free grains selected for abrasion to yield the most concordant fraction.



FIG. 16. Above grains abraded with pyrite to produce a clean polished surface. Dark outer rims are due to refraction of light.

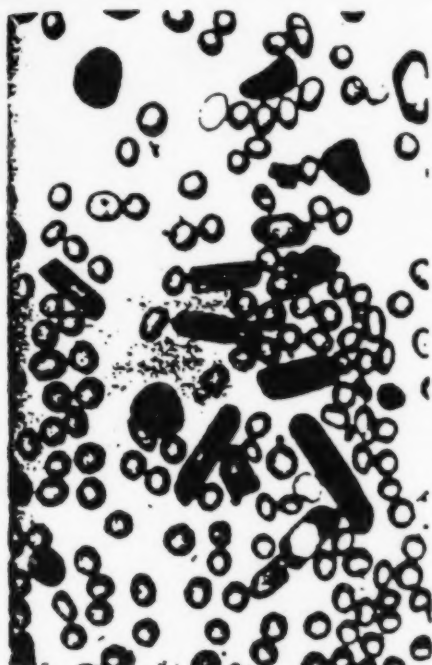


FIG. 16. Relative hardness of zircon (elongate) pyrite (angular rounded) and apatite (round) are shown by the degree of rounding after abrasion together.



FIG. 16. Altered (hydrated botryoidal) zones are common in the outer uranium rich margins of sample 504, and other zircons with sufficient radiation damage. Altered parts, rounded, dark gray forms after HF vapour etch.

Clean beakers (boiled in HCl acid for a week), are checked for contaminants and covered with parafilm and numbered very carefully.

Individual grains or batches of grains are transferred to each beaker with a pipette and alcohol.

Remove excess alcohol with a pipette, the alcohol must not be allowed to evaporate as it will leave a sticky residue. Finally take to the chemistry lab.

Dissolution is carried out in Teflon TM vessels using 0.1-0.5ml of high purity 48% HF and 0.01ml of high purity 70% HNO₃. The vessels are sealed and heated in an oven at 230-240°C for 30-60 hours (for zircon, baddelyite, rutile and thorite). Monazite is dissolved in 12N HCL at 150-180°C for 30-60 hours. Sphene, allanite, garnet and apatite are processed in 3ml Savillex TM screw cap vessels placed inside 125ml Teflon TM dissolution containers and heated for about 30 hours at 210°C, or 24 hours on a hot plate at about 150°C.

Column chemistry

Element separation using anion exchange chemistry is descibed in detail by Parrish et al.(1987).

Pb is separated on anion exchange columns in 1N HBr and 6.2N HCL, and U is purified using another exchange column in 8N HNO₃, and eluted with H₂O.

Blanks for Pb and U are 6-40pg and <10pg respectively.

Mass spectrometry

Isotopic compositions of Pb and U are measured on a 354 VG solid source mass spectrometer and are individually scanned on a continuous basis.

Lead and uranium fractions are loaded as, respectively, phosphate or nitrate, onto a single degassed Rhenium filament using the silica gel method. Filaments are loaded into the mass spectrometer (Figure 17) and after the vacuum of 10⁻⁶-10⁻⁹mm Hg has been achieved (the better the vacuum the better the results) the filament is heated to temperatures in the range 1480-1700°C (uranium only comes off above 1550°C and by temperatures of 1620-1640°C the sample is dead. The element is volatilized at these temperatures and ions are accelerated, collimated into a beam and collected at the analyzer. The analyzer can be a Daly or Faraday Cup type depending on size of sample used.

Data collected is then processed and plotted on concordia/discordia (²⁰⁶Pb*/²³⁸U v ²⁰⁷Pb*/²³⁵U) diagram.

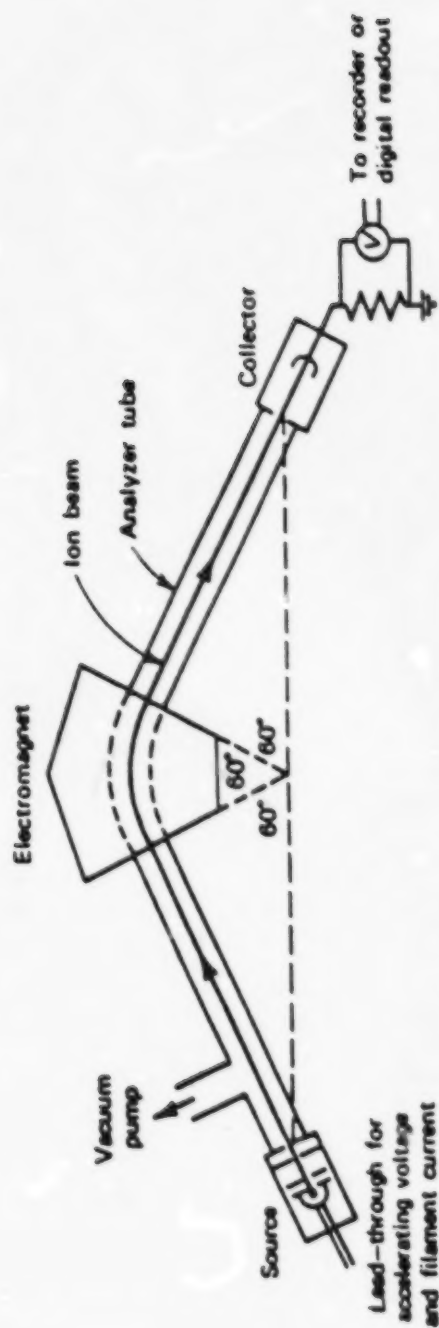


FIGURE 17 Schematic diagram of a 60° sector mass spectrometer showing arrangement of ion source, electromagnet, and collector.

From Faure (1986)

Appendix C

Fluid inclusion microthermometric analysis .

A fluid inclusion microthermometric study to determine parameters such as $T_m \text{ CO}_2$ (final melting point of CO_2), $T_e \text{ ice}$ (initial melting point of ice), $T_m \text{ ice}$ (final melting point of ice), $T_m \text{ h}$ (melting point of salt hydrates), $T_m \text{ clath}$ (final melting point of clathrate), $T_h \text{ CO}_2$ (homogenization temperature of CO_2), $T_h \text{ total}$ (final homogenization temperature of the inclusion), fluid composition etc., will be determined from fluid inclusions in the various quartz vein phases associated with the Arcadia Bay mineralization and from samples of least deformed tonalite, the Chin Lake and Arcadia Bay stocks, and the late phase of WNW trending pegmatite dikes. Detailed petrographic analysis of host minerals and fluid inclusions will be carried out, paying particular attention to the effects of strain features, using a preliminary classification of microtextures from Spooner et al. (in prep.). The purpose of this analytical approach is: a) Determine the temperature of the fluid from which the Arcadia Bay mineralization precipitated ($T_h \text{ total}$) either by direct measurement, if coexisting and cogenetic liquid- and gas-rich inclusions are present and they homogenize into either the liquid or the gas at the same temperatures, the same applies for CO_2 - and H_2O -rich inclusions (e.g. Wood et al., 1986; Burrows and Spooner, 1987; Thomas et al., 1988) or by pressure correction for $T_h \text{ total}$ values using isochores (e.g. Thomas and Spooner, 1988).; b) Determine if boiling or phase separation occurred at the site of mineral precipitation; c) A qualitative indication of the dominant salts in the system can be made using $T_e \text{ ice}$ (Crawford, 1981); d) Determine the bulk composition of the aqueous phase in the inclusion using $T_m \text{ h}$ (Crawford et al., 1979, Haynes, 1985); e) Derive an apparent salinity (in equivalent wt% NaCl) of the fluid using $T_m \text{ ice}$ (Potter et al. 1978, Hall et al., 1988). In CO_2 and CH_4 -bearing inclusions $T_m \text{ clath}$ is used to derive the salinity of the fluid (Bozzo et al. 1973; Thomas and Spooner, 1988); f) Derive quantitative information on the amounts of additional components present eg. N_2 and CH_4 ($T_m \text{ CO}_2$); h) Determine the density of the CO_2 phase (Angus et al. 1976) and i) attempt to relate magmatic fluids from the tonalite, quartz monzonite stocks and pegmatites with those in the mineralized quartz veins. Before fluid inclusion studies can be applied to geological problems three basic premises need to be established:

- 1) Some of the fluid inclusions must be primary,
- 2) Because only primary inclusions are truly representative of the fluids present during primary growth, and
- 3) The inclusions behaved as closed systems; nothing was added or removed from the inclusions since trapping.

All fluid inclusion measurements will be carried out on a Linkam Scientific Instruments TH600 programmable heating/cooling stage (Shepherd, 1981; see Figure 18) and a fluid inclusion data sheet filled out (Figure 19). Calibration of the stage over the temperature range required is explained in Macdonald and Spooner (1981) and the fluid inclusions are measured in 60-200 μm doubly polished sections prepared according to a method modified from that of Holland et al. (1978).

Fluid inclusion studies, combined with mineral paragenetic, and light stable isotope studies, may reveal a thermal evolution of the fluids e.g. Kamilli and Ohmoto (1977) showed that boiling caused the formation of high grade bonanza ore shoots in the Finlandia vein, Peru; Casadevall and Ohmoto (1977) suggested that the isotopic evidence showed that hydrothermal solutions producing the caldera related vein systems of Sunnyside, Colorado, were dominantly of meteoric origin.

Pressure correction

A knowledge of the pressure at the time of trapping is important in two respects:

- 1) it provides information of intrinsic geological significance, and
- 2) it provides a means of correcting homogenization temperatures to obtain true trapping temperatures ('Pressure Correction'). Pressure correction is the difference ($T_T - T_H$) and is a function of pressure, density and salinity (See Figures 20 and 21). Homogenization temperatures are usually a minimum estimate of trapping temperatures, the difference being a function of the trapping pressure. In order to estimate the pressure, both the composition and the PVTX properties of the fluid are needed. Four principal methods are used:

1) Vapour pressure of the fluid at T_H

This method, modelled on the system $\text{NaCl-H}_2\text{O}$, estimates the absolute pressure minimum, and values of T_H and salinity are compared to those on tables of data. For two-phase (L+V) aqueous inclusions, unless the fluid was trapped on the liquid/vapour curve (ie. Boiling) the true pressure lies at any point along an isochore originating at T_H (Figure 22).

2) Fluid isochore+independent geothermometer.

This is an extension of the above method and uses an estimate of the trapping temperature to define a position along the isochore originating at T_H . The fluid density and slope of the isochore are calculated and by estimating the trapping temperature, using another (pressure-independent) geothermometer (e.g. stable isotope geothermometers) the corresponding pressure estimate can be read off along the appropriate isochore (Figure 22).

3) Dissolution of halite daughter minerals.

Halite-bearing inclusions homogenize in one of three ways:

- i) halite dissolves before disappearance of vapour bubble ($T_{\text{NaCl}} < T_H$);
- ii) simultaneous disappearance of halite and vapour ($T_{\text{NaCl}} = T_H$);

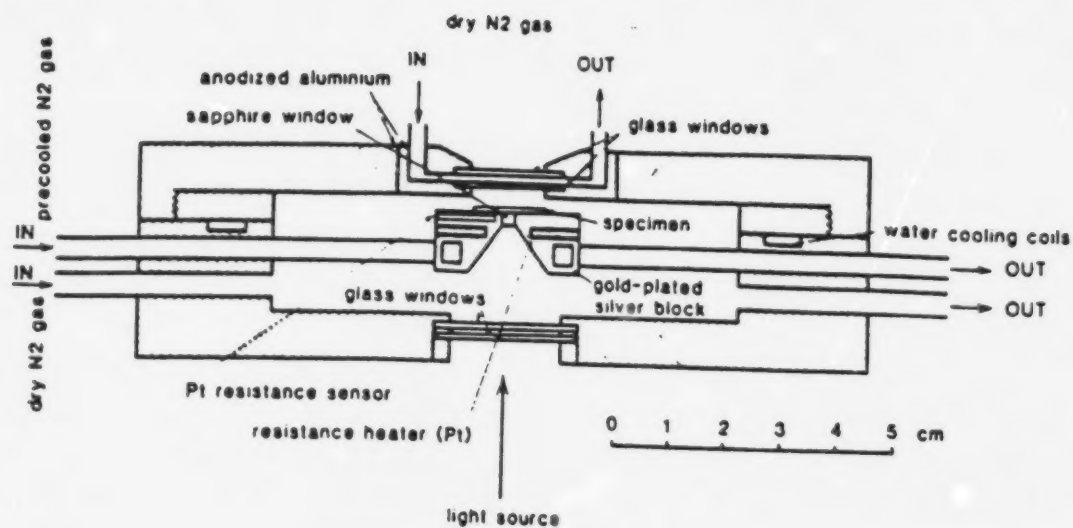


Figure 18 Cross-section of Linkam stage.

From Shepherd et al. (1985)

FLUID INCLUSION DATA SHEET

SAMPLE NO

AREA NO

INCLUSION NUMBER

FROM D.CHANNER.

DATE								
OCCURRENCE								
SIZE (μm) & SHAPE								
T _{MIN} (lowest temp to which inclusion is taken)								
T _g (temp at which first melt appears)								
T _M - CO ₂								
- - - - -								
- CLATH								
- - - - -								
- HYD								
- - - - -								
- ICE								
- - - - -								
- DM								
BUBBLE SIZE (μm) at 40°C								
BUBBLE VOL% (inner phase of mixed inclusion)								
T _M - (1) CO ₂								
- - - - -								
- (2) TOTAL								
T _d (decrepitation temp)								
Comments. NB: (1) Record all phases present at phase changes (2) Heating rate at all phase changes = 0.4°C/min unless otherwise stated								

Figure 19

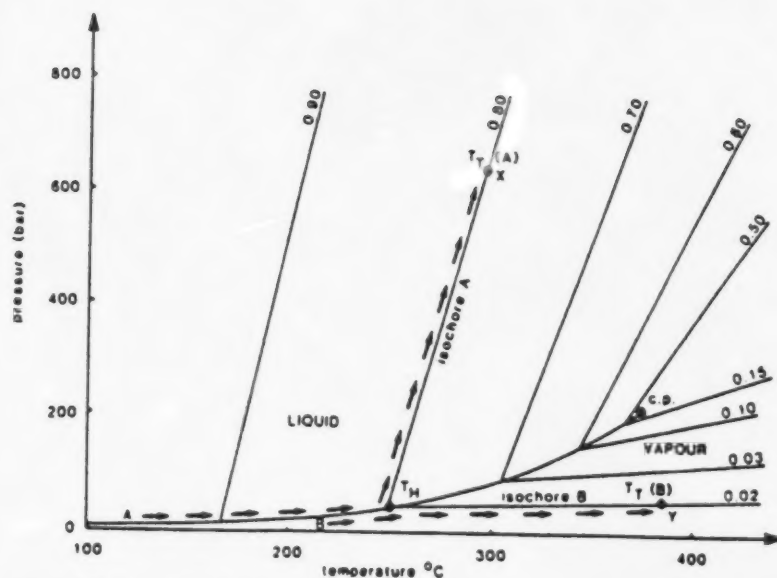


Figure 20 P-T diagram for pure water indicating the reheating paths taken by inclusions A and B which homogenize at the same temperature (T_H) but have different bulk densities. See text for details. The fine lines are isochores and are labelled in g cm^{-3} . The heavy line terminating at the critical point c.p. is the liquid-vapour curve. Note that for a given pressure the difference ($T_T - T_H$) increases as the density decreases because the isochores are flatter (T_T , trapping temperature).

From Shepherd et al. (1985)

Table 2. Petrographic and geochemical characteristics of Archean TTG's

IUGS classification	Major mineral percentages	Comments
Trondhjemite, A light-colored plutonic rock primarily composed of sodic plagioclase (esp. oligoclase), a quartz diorite with oligoclase as the sole feldspar.	Plagioclase = oligoclase or andesine. Quartz = $\geq 20\%$ of leucocratic minerals. K'spr. = $\leq 10\%$ of total feldspar. Color index = ≤ 10	Barker (1979), suggests addition of calcic-trondhjemite for Andesine-bearing and albite/oligoclase-bearing leucotonalite be classified as trondhjemite.
Tonalite, a plutonic rock with Q between 20 and 60, and $P/(A+P) > 90$. Synonymous with quartz-mica-diorite	Plagioclase (An 30) 72%, Microperthite 11%, quartz 7%, mafics and accessories 10%.	
Major elements	Trace and REE's	Comments.
SiO ₂ Range between 62-70%. Al ₂ O ₃ High alumina-type >15% @ 70% SiO ₂ . Low alumina are volumetrically insignificant. (FeO+MgO)<3.4%, and FeO:MgO 2-3. CaO 4.4-4.5% in calcic trondhjemites.to typical values of 1.5-3.0. Na ₂ O 4.0-5.5%. K ₂ O $\leq 2.5\%$	Steeply fractionated REE patterns (La _N /Yb _N ~20-100) with weak to absent Eu anomalies and depleted HREE's (Yb < 8X chondrite)	Exhibit calc alkaline and trondhjemitic calc alkaline trends on AFM and QAP diagrams, Na-enrichment and straddle the TTG region on An-Or-Ab plots.

Table 3 Accessory and major phase minerals and their affects on magmas due to their REE substitution affects

Name and formula	Trace and REE Substitution	Affects on REE content in melt
Zircon $\text{Zr}(\text{SiO}_4)$	Hf Nb Ta Y	Large KD's for REE's. Hanson (1978), suggests that if in sufficient quantities zircon may have a large effect on the depletion of HREE's. Buma et al.(1971), suggested that residual zircon may explain steep REE patterns in Archean TTG's.
Baddeleyite ZrO_2	Same as zircon	Similar to zircon
Allanite $(\text{CaCe})_2(\text{Fe}^{2+}, \text{Fe}^{3+})$ $\text{Al}_2\text{O}_3\text{OH}[\text{Si}_2\text{O}_7][\text{SiO}_4]$	Ca substituted by Ce and other REE's particularly La, Y, Th La more readily substitutes in allanite over Y and Sm because of charge and size differences. Because LREE's are major stoichiometric constituents of Allanite they affect its stability and growth.	Allanite is very efficient at extracting LREE's from the magma in high silica rhyolites and in the Peninsular range Batholith (Mahood and Hildreth, 1983; Gromet and Silver 1983). Gromet and Silver (op cit), have shown that 80-90% of each REE is taken up by Allanite which also exhibits REE zoning. This is seen in core-rim decrease in Ce contents of ~25% and similar decreases in La and Nd but an increase in Th.

Geochemistry

Calculated CIPW normative values for each sample will be used in conjunction with major element data plotted on standard AFM, An-Or-Ab (O'Connor, 1965; Barker, 1979), and QAP (Strekeisen, 1973; Lameyre and Bowden, 1982) triangular diagrams.

INAA methodology

In Instrumental Neutron Activation Analysis (INAA) nuclear bombardment reactions are used to determine the concentrations of REE's (La, Nd, Sm, Yb, Lu, Ce, Eu, Tb) and trace elements (Ba, U, Th, Co, Cs, Sc, Hf, Ta) in geological samples. The nuclear bombardment irradiates the sample increasing the neutron number of the product nucleus by 1 with respect to the target nucleus the atomic number (Z) of the product remains unchanged and is therefore an isotope of the target. The product decays by emitting gamma rays and the activity of each product/isotope is strongly dependent on the concentration of the target element. To determine the concentration of an element in a sample of known weight the sample is irradiated with slow neutrons along with a standard containing a known amount of the same element. At the University of Toronto Slowpoke 2 reactor sample and standard powders are, placed in plastic sachets and sealed. Ten to fifteen of these are placed in a polyethylene tube and irradiated. The activity of the irradiated sample and standard is counted at intervals of 7 and 40 days. For further details on counting intervals and computation of results see Froggat (1985). Rare-earth and trace element modelling has been used as a powerful tool for the quantification of fractional crystallization and partial melting and samples from the Arcadia Bay area will be analysed by INAA using the Slowpoke 2 Research Reactor facility at the University of Toronto. Rare-earth element data will be normalized (N) to the chondritic values determined by Haskin et al. (1968) and Nakamura (1974), as recommended by Rock (1987), and are plotted on REE distribution diagrams (e.g. Figure 6). Care must be taken in choosing the normalizing material, values, and element order when using multi-element diagrams (spidergrams; Rock, 1987).

XRF analysis

XRF analysis is carried out as certain elements are not amenable to INAA these include Ni, Cr, V, Rb, Sr, Zr, Y, and N, sample amounts used are approximately 2-3g.

X-ray fluorescence analyses will be carried out at the University of Toronto using rock powders ground in an alumina mill to prevent contamination from iron and chrome. Major elements will be analyzed using fused glass discs, any iron present is oxidized by adding 20mg of ammonium nitrate to the rock powders. The mixture plus fusion flux is heated in a platinum crucible, when completely liquid and homogeneous it is poured into a platinum mold and quenched. Trace elements are analyzed as powder pellets using boric acid as a sample casing.

Samples and standards are run on a Siemens X-ray fluorescence unit according to the procedures outlined by Norrish and Chappell (1977). All major and trace samples are run in duplicate, using either a chrome-anode or molybdenum X-ray tube respectively.

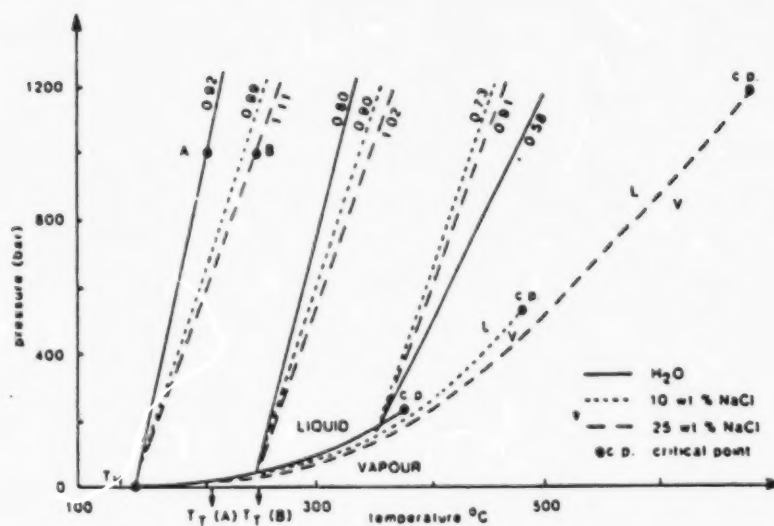


Figure 21 Influence of salinity on the position of the liquid-vapour curve and slope of the isochors in the liquid field for the system $\text{H}_2\text{O}-\text{NaCl}$. Isochores are labelled in g cm^{-3} . Other abbreviations as for Figure 4.3.

From Shepherd et al. (1985)

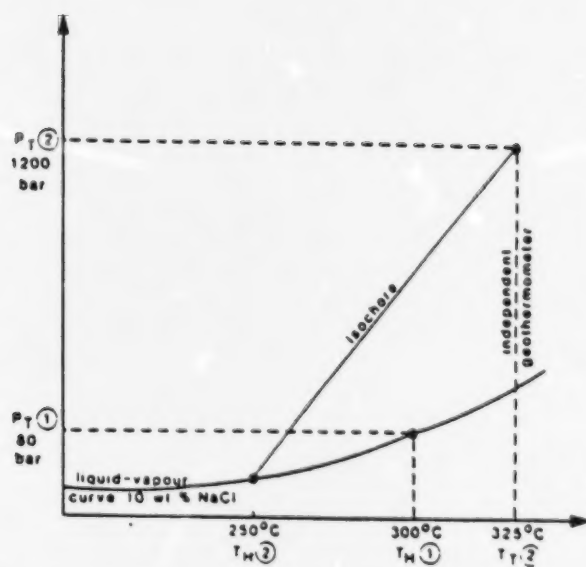


Figure 22 Pressure estimates based on the vapour pressure of the fluid at T_H and the use of an independent geothermometer in conjunction with the fluid isochore. See text for explanation.

From Shepherd et al. (1985)

iii) halite dissolves after disappearance of vapour ($T_h < T_{sNaCl}$).

Assuming no boiling, the pressure estimates given by each form of homogenization are minima since the inclusions could have formed at any point along isochores A, B and C in Figure 23.

As shown by Shepherd et al. (1985) the third case provides a better temperature estimate and if the P-T conditions at T_{sNaCl} are known it would give a better estimate of the trapping temperature.

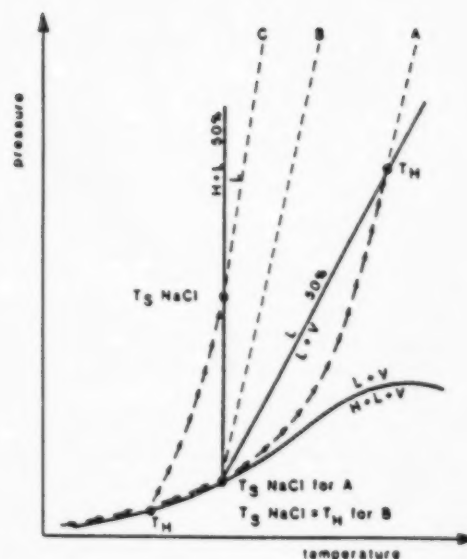


Figure 23 Idealized $P - T$ section through the system $H_2O - NaCl$ showing the three principal modes of halite dissolution ($T_S NaCl$) with respect to vapour disappearance (T_H) for halite-bearing inclusions. Path A: $T_S NaCl < T_H$; path B: $T_S NaCl = T_H$; path C: $T_S NaCl > T_H$. Curve H + L-L is the liquidus curve for a 50% NaCl solution. Curve L-L + V is the liquid-vapour curve (highly exaggerated). Curve L + V-L + V + H is the three-phase halite-saturated, liquid-vapour curve. Dashed lines represent isochoric paths in the liquid field for inclusions which follow homogenization paths A, B and C. Arrowed paths are the isochoric paths for the same inclusions prior to total homogenization.

From Shepherd et al. (1985)

Table 4 Summary of fluid inclusion data for Archean gold deposits in the Abitibi Subprovince (Canada) and the Yilgarn Block (Australia). Modified from Colvine et al.(1988).

Deposit or Area	Fluid Inclusion Data	Interpretation
Red Lake, Ontario. Brown and LaKind (1986).	Primary, low salinity H ₂ O-CO ₂ ; higher CO ₂ density; Variable CO ₂ /H ₂ O ratios; Th=110°-360°C; Gold related. Secondary: aqueous brine; Th=>350°C. Secondary low salinity (<10equiv. wt% NaCl), CO ₂ -H ₂ O low CO ₂ density.	Possible fluid unmixing
Hollinger-McIntyre Mine, Ontario.Smith et al.(1984)	Pseudo secondary or primary H ₂ O-CO ₂ , Th=220°-385°C, 3-24 mole wt% CO ₂ , CO ₂ liq phase homog., CO ₂ density range 0.46to 0.78g/cm ³ . Gold related Secondary CO ₂ -bearing aq. incs, Th=160°-215°C. In graphite-bearing vein, pseudo secondary to primary CH ₄ -CO ₂ -H ₂ O incs. (>26 mole % CH ₄). Secondary CH ₄ -rich incs.	Possible fluid immiscibility, fluids buffered by QFM. Depositional pressure 0.35 to 0.5bars.
Hollinger-McIntyre Mine, Ontario Wood et al.(1986)	Primary H ₂ O-CO ₂ , variable phase proportions; 6 mole %CO ₂ ; Th=225°-355°C; mean 277°C; Minor CH ₄ ; CO ₂ density 0.65g/cm ³ .	Phase separation
Sigma Mine, Val d'Or, Quebec. Robert and Kelly (1987).	Secondary H ₂ O-CO ₂ incs. with <10 eqv. wt% NaCl, 15-30 mole % CO ₂ ; Th=285°-395°C. Coexisting H ₂ O-rich incs.,25-34eqv wt% NaCl, Th= 60°-295°C and CO ₂ -rich incs. in healed fractures	Fluid unmixing intermittently.

Yilgarn-Block, Australia.Ho et al.(1985)	Primary H ₂ O-CO ₂ with both constant and variable phase proportions (20 -30 mole% CO ₂), <2eqv. wt% NaCl, Th=200°-390°C.	Early fluid, some unmixing.
	Coexisting primary H ₂ O-rich and CO ₂ -rich in late vugs.	Late fluid, heterogeneous.
O'Brien Mine, Cadillac, Quebec.Krupka et al..(1977).	Primary H ₂ O-CO ₂ incs. with constant phase proportions.	Early fluid homogeneous
	Coexisting secondary H ₂ O-CO ₂ ; Th of both types = 210°-380°C.	Late heterogeneous fluid.
Renabie Mine, Ontario. Studemester and Kilias (1987)	Three types of primary inclusion (1). aqueous with 10-25 vol.% CO ₂ density of 0.75g/cm ³ Th= 220°-360°C.(2). ~100 vol.% CO ₂ , density = 0.95 g/cm ³ . (3). aqueous with 10-50 vol.% H ₂ O gas. Th= 120°-220°C. Apparent salinities are 4- 8, 0, and 11-14 eqv wt % NaCl respectively.	Two to three generations of fluids produced during greenschist metamorphism (?). They may also represent immiscible CO ₂ and NaCl-H ₂ O phases
Pamour Mine, Ontario Walsh et al. (1988).	Two types of primary inclusions in sphalerite directly associated with high-grade gold contain CO ₂ -CH ₄ fluid (20-45 mole% CH ₄), and H ₂ O-rich liquid with a carbonaceous phase (CO ₂ -CH ₄). Aqueous phase salinity estimates range from 2-9 eqv. wt.% NaCl and CaCl ₂ with lesser amounts of KCl, MgCl ₂ , S, Zn,and Fe	These inclusion types appear to represent immiscible fluids trapped along the solvus in the H ₂ O-CO ₂ -CH ₄ -salt system at temperatures of 325°± 25°C and pressures of 1-2 kb.

Appendix D

Stable Isotope Analysis of Fluid Inclusions and selected minerals.

The combined use of stable isotopes with other isotopic systems provides increased constraints on mineral forming processes. $\delta^{34}\text{S}$, $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and δD from carbonate in the late phase quartz veins, quartz veins, fluids extracted from fluid inclusions in quartz veins, and sulfides. With temperature constraints imposed by fluid inclusion studies, $\delta^{18}\text{O}$ water initial may be estimated. Values of -3.8 and -4.1 ‰ $\delta^{13}\text{C}$ are thought to reflect a magmatic carbon source (Stakes and O'Neill, 1982). Similar values have been obtained for the Hollinger/McIntyre gold deposits (Burrows et al., 1986) and those from the Barberton (de Ronde et al., 1988). Values of -35‰ to +2‰ and -34‰ to -6.9‰ have been suggested to represent a metamorphic source (Burrows and Spooner, 1988; Vry et al, 1988) Comparison of values obtained for the Arcadia Bay deposit with the Hollinger-McIntyre and Barberton deposits will enable the author to test whether the Arcadia Bay fluids have similar signatures

Hydrogen

Vacuum crushing of 4-5g of acid washed quartz containing inclusions releases volatiles which are then frozen in a liquid N_2 cold trap via an evacuated tube. Condensable gases such as H_2O and CO_2 could be further separated by substituting the liquid N_2 for alcohol plus dry ice (CO_2), thus the H_2O is retained which allows CO_2 to be frozen down in another liquid N_2 cold trap. Approximately 3 microlitres of H_2O are needed for δD analysis on the VG mass spectrometer. The problem of H_2O condensation in the evacuated tube, when volatiles are released from the furnace, is overcome by heating the tubes from the furnace to the cold traps to slightly above 100°C . Using the method of Coleman et al. (1982) a 1-10mg sample of water is reduced with zinc metal in a sealed, evacuated tube at 450°C (Figure 24) to prepare hydrogen for isotopic analysis. After reaction the tube is directly attached to the mass spectrometer without further processing. Values obtained are measured against a reference gas produced from Vienna SMOW (V-SMOW, zero point of the δD scale), but corrected for the valve mixing and H_3 contribution to the HD ion beam.

Carbon

Carbon isotope measurements are made on CO_2 (e.g. Craig, 1957). CO_2 is liberated from most carbonates by reaction with 100% phosphoric acid at 25°C (McCrea, 1950). Carbonates that react very slowly with phosphoric acid can also be treated by thermal decomposition in BrF_5 systems (Sharma and Clayton, 1965). The standard used is PDB (belemnite from the Cretaceous Peedee-formation, South Carolina).

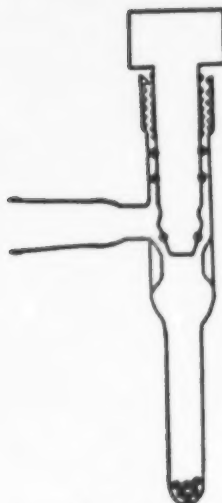


Figure 24 The water reduction tube. The zinc shot and water are introduced by completely removing the screwed Teflon plug.

Apparatus. The principal item of apparatus, shown in Figure , is a simple tube, 12.5 mm outside diameter, 9.2 mm internal diameter, and 70 mm long, made by sealing off a high vacuum, 90° pattern, high vacuum stopcock (Model 8196-47, Ace Glass Inc., Vineland, NJ) to which has been added a standard taper B14 socket to allow attachment to either a vacuum line or a mass spectrometer. The stopcock, which is sealed with elastomer "O" rings, has a plug and handle made only from Teflon which allows high-temperature operation.

From Coleman et al. (1982)

Oxygen

Because of the higher abundance and the greater mass difference, the $^{18}\text{O}/^{16}\text{O}$ ratio is normally determined. Standard Mean Ocean Water (SMOW) has a value in absolute numbers of 1:475 to 1:525.

Oxygen in silicates and oxides is liberated by converting oxygen to CO_2 with F_2 or BrF_5 in nickel tubes at $500^\circ\text{--}600^\circ\text{C}$. Decomposition by carbon reduction at $1000^\circ\text{--}2000^\circ\text{C}$ is suitable for quartz and iron oxides but not for silicates. Unwanted product gases are removed from the oxygen by cold traps, and excess F_2 is removed by reaction with KBr to form KF and Br_2 which is condensable. The latter procedure is not necessary when BrF_5 is used. The oxygen is converted to CO_2 over a heated graphite rod. Carbonates are reacted with 100% phosphoric acid at various temperatures between 25° and 75°C .

Sulfur

The standard reference for the $\delta^{34}\text{S}$ isotope is from troilite of the Canon Diablo iron meteorite.

The gas used in mass spectrometric analysis is usually SO_2 . Pure sulfides are converted to SO_2 by reaction with an oxidising agent (CuO , Cu_2O , V_2O_5 , and O_2). Combustion with a solid oxidant in vacuum minimizes the presence of contaminant gases, particularly CO_2 , and purification of the SO_2 is often unnecessary.